Atomic Transactions

- Transaction
  - An operation composed of a number of discrete steps.
  - All the steps must be completed for the transaction to be committed. The results are made permanent.
  - Otherwise, the transaction is aborted and the state of the system reverts to what it was before the transaction started.
    - rollback = reverting to a previous state

Example

- Buying a house:
  - Make an offer
  - Sign contract
  - Deposit money in escrow
  - Inspect the house
  - Critical problems from inspection?
  - Get a mortgage
  - Have seller make repairs
  - Commit: sign closing papers & transfer deed
  - Abort: return escrow and revert to pre-purchase state

All or nothing property

Basic Operations

Transaction primitives:

- Begin transaction: mark the start of a transaction
- End transaction: mark the end of a transaction – no more tasks
- Commit transaction: make the results permanent
- Abort transaction: kill the transaction, restore old values
- Read/write/compute data (modify files or objects)
  - But data will have to be restored if the transaction is aborted.

Properties of transactions: ACID

- Atomic
  - The transaction happens as a single indivisible action. Everything succeeds or else the entire transaction is rolled back. Others do not see intermediate results.
- Consistent
  - A transaction cannot leave the database in an inconsistent state. E.g., total amount of money in all accounts must be the same before and after a "transfer funds" transaction.
- Isolated (Serializable)
  - Transactions cannot interfere with each other or see intermediate results if transactions run at the same time, the final result must be the same as if they executed in some serial order.
- Durable
  - Once a transaction commits, the results are made permanent. Failures after a commit will cause the results to revert.

Another Example

- Book a flight from Newark, New Jersey to Inyokern, California. No non-stop flights are available:

  Transaction begin
  1. Reserve a seat for Newark to Denver (EWR→DEN)
  2. Reserve a seat for Denver to Los Angeles (DEN→LAX)
  3. Reserve a seat for Denver to Inyokern (LAX→IYK)
  Transaction end

If there are no seats available on the LAX→IYK leg of the journey, the transaction is aborted and reservations for (1) and (2) are undone.
Distributed Transactions

- Transaction that updates data on two or more systems

- Challenge
  - Handle machine, software, & network failures while preserving transaction integrity

Distributed Transactions

- Each computer runs a transaction manager
  - Responsible for subtransactions on that system
  - Transaction managers communicate with other transaction managers
  - Performs prepare, commit, and abort calls for subtransactions

  Every subtransaction must agree to commit changes before the overall transaction can complete

Commits Among Subtransactions = Consensus

- Remember consensus?
  - Agree on a value proposed by at least one process

- The coordinator proposes to commit a transaction
  - All participants agree ⇒ all participants then commit
  - Not all participants agree ⇒ all participants then abort

  Here, we need unanimous agreement to commit

Two-Phase Commit Protocol

Goal:
Reliably agree to commit or abort a collection of sub-transactions

- All processes in the transaction will agree to commit or abort

- One transaction manager is elected as a coordinator – the rest are participants

  Assume:
  - write-ahead log in stable storage
  - No system dies forever
  - Systems can always communicate with each other

Two-Phase Commit Protocol

- Coordinator
  - Participates in each subtransaction
  - Proposes to commit or abort the collection of sub-transactions

- Participants
  - Execute the subtransactions
  - Communicate with the coordinator to agree on the commit or abort decision

- Relationship between Coordinator and Participants:
  - The Coordinator initiates the Prepare phase and receives the PrepareRequest from all Participants.
  - Once all Participants have responded with PrepareReceipt, the Coordinator initiates the Commit phase and sends to all Participants.
  - Each Participant verifies the CommitRequest and decides whether to commit or abort, based on the local state.
  - The Coordinator collects the responses and decides to commit or abort the collection of sub-transactions based on the aggregated responses from all Participants.
When a participant enters the **prepared** state, it contacts the coordinator to start the commit protocol to commit the entire transaction.

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**Transaction States**

- **started**
- **working**
- **prepared** (done)
- **committed**
- **aborted**

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**Two-Phase Commit Protocol**

**Phase 1: Voting Phase**
Get commit agreement from every participant

- **Coordinator**
- **Participant**
- **Participant**
- **Participant**
- **Participant**

A single “no” response means that we will have to abort the transaction.

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**Two-Phase Commit Protocol**

**Phase 2: Commit Phase**
Send the results of the vote to every participant

- **Coordinator**
- **Participant**
- **Participant**
- **Participant**
- **Participant**

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**Dealing with failure**

- **2PC assumes a fail-recover model**
  - Any failed system will eventually recover

- A recovered system cannot change its mind
  - If a node agreed to commit and then crashed, it must be willing and able to commit upon recovery

- Each system will use a write-ahead (transaction) log
  - Keep track of where it is in the protocol (and what it agreed to)
  - As well as values to enable commit or abort (rollback)
  - This enables fail-recover
Two-Phase Commit Protocol: Phase 1

**Voting Phase**
- Coordinator:
  - Write prepare to commit to log
  - Send prepare to commit message
  - Wait for all participants to respond

- Participant:
  - Write prepare to commit to log
  - Send prepare to commit message
  - Wait for message from coordinator
  - When ready, write agree to commit or abort to the log
  - Send agree to commit or abort to the coordinator

Get distributed agreement: the coordinator asked each participant if it will commit or abort and received replies from each coordinator.

Voting Phase

- Coordinator:
  - Receive the prepare message

- Participant:
  - Work on transaction

Two-Phase Commit Protocol: Phase 2

**Commit Phase**
- Coordinator:
  - Wait for commit/abort message
  - Receive commit or abort
  - Send commit or abort

- Participant:
  - Write commit or abort to log
  - Wait for commit/abort message
  - When ready, write agree to commit or abort to the log

Tell all participants to commit or abort

Get everyone's response that they're done.

Dealing with failure

- Failure during Phase 1 (voting)
  - Coordinator dies
    - Some participants may have responded; others have no clue
    - Coordinator restarts; checks log; sees that voting was in progress
    - Coordinator restarts voting
  - Participant dies
    - The participant may have died before or after sending its vote to the coordinator
    - If the coordinator received the vote, wait for other votes and go to phase 2
    - Otherwise: wait for the participant to recover and respond (keep querying it)

- Failure during Phase 2 (commit/abort)
  - Coordinator dies
    - Some participants may have been given commit/abort instructions
    - Coordinator restarts; checks log; informs all participants of chosen action
  - Participant dies
    - The participant may have died before or after getting the commit/abort request
    - Coordinator keeps trying to contact the participant with the request
    - Participant recovers; checks log; gets request from coordinator
    - If it committed/aborted, acknowledge the request
    - Otherwise, process the commit/abort request and send back the acknowledgement

Adding a recovery coordinator

- Another system can take over for the coordinator
  - Could be a participant that detected a timeout to the coordinator
  - Recovery node needs to find the state of the protocol
    - Contact all participants to see how they voted
    - If we get voting results from all participants
      - We know that Phase 1 has completed
      - If all participants voted to commit, send commit request
      - Otherwise send abort request
    - If ANY participant states that it has aborted
      - We know that Phase 1 has not completed
      - Restart the protocol
  - But... if a participant node also crashes, we're stuck!
    - Have to wait for recovery

What’s wrong with the 2PC protocol?

- Biggest problem: it's a blocking protocol with failure modes that require all systems to recover eventually
  - If the coordinator crashes, participants have no idea whether to commit or abort
  - A recovery coordinator helps
  - If a coordinator AND a participant crashes
    - The system has no way of knowing the result of the transaction
  - It might have committed for the crashed participant – hence all others must block
  - When a participant gets a commit/abort message, it does not know if every other participant was informed of the result
Three-Phase Commit Protocol

- Same setup as the two-phase commit protocol:
  - Coordinator & Participants
- Add timeouts to each phase that result in an abort
- Propagate the result of the commit/abort vote to each participant before telling them to act on it
  - This will allow us to recover the state if any participant dies

Three-Phase Commit Protocol: Phase 1

- Phase 1: Voting phase
  - Coordinator sends canCommit? queries to participants & gets responses
  - Purpose: Find out if everyone agrees to commit
  - If the coordinator gets a timeout from any participant, or any NO replies are received
    - Send an abort to all participants
  - If a participant times out waiting for a request from the coordinator
    - It aborts itself (assume coordinator crashed)
  - Else continue to phase 2

We can abort if the participant and/or coordinator dies

Three-Phase Commit Protocol: Phase 2

- Split the second phase of 2PC into two parts:
  2a. "Precommit" (prepare to commit) phase
    - Send Prepare message to all participants when it received a yes from all participants in phase 1
    - Participants can prepare to commit but cannot do anything that cannot be undone
    - Participants reply with an acknowledgement
    - Purpose: let every participant know the state of the result of the vote so that state can be recovered if anyone dies
  2b. "Commit" phase (same as in 2PC)
    - If coordinator gets ACKs for all prepare messages
      - It will send a commit message to all participants
    - Else it will abort – send an abort message to all participants

Three-Phase Commit Protocol: Phase 3

- Phase 3: Finalize phase
  - Send commit messages to participants and get responses from all
  - [!] If participant times out: contact any other participant and move to that state (commit or abort)
  - [!] If coordinator times out: that’s ok – we know what to do

3PC Recovery

- If the coordinator crashes
  - A recovery node can query the state from any available participant
- Possible states that the participant may report:
  - Already committed
    - That means that every other participant has received a Prepare to Commit
    - Some participants may have committed
    - Send Commit message to all participants (just in case they didn’t get it)
  - Not committed but received a Prepare message
    - That means that all participants agreed to commit; some may have committed
    - Send Prepare to Commit message to all participants (just in case they didn’t get it)
    - Wait for everyone to acknowledge, then commit
  - Not yet received a Prepare message
    - This means no participant has committed; some may have agreed
    - Transaction can be aborted or the commit protocol can be restarted

Paul Krzyzanowski
3PC Weaknesses

- Main weakness of 3PC
  - May have problems when the network gets partitioned
  - Partition A: nodes that received Prepare message
    - Recovery coordinator for A: allows commit
  - Partition B: nodes that did not receive Prepare message
    - Recovery coordinator for B: aborts
  - Either of these actions are legitimate as a whole
    - But when the network merges back, the system is inconsistent
- Not good when a crashed coordinator recovers
  - It needs to find out that someone took over and stay quiet
  - Otherwise it will mess up the protocol, leading to an inconsistent state

3PC coordinator recovery problem

- Suppose
  - a coordinator sent a Prepare message to all participants
  - all participants acknowledged the message
  - BUT the coordinator died before it got all acknowledgements
- A recovery coordinator queries a participant
  - Continues with the commit: Sends Prepare, gets ACKs, sends Commit
- Around the same time... the original coordinator recovers
  - Realizes it is still missing some replies from the Prepare
  - Gets timeouts from some and decides to send an Abort to all participants
- Some processes may commit while others abort!
- 3PC works well when servers crash (fail-stop model)
- 3PC is not resilient against fail-recover environments

What about Paxos?

- Interface to Paxos
  - Client proposes a value and sends it to the Paxos leader
  - Paxos acceptors will send out the totally-ordered value
- What does Paxos consensus offer?
  - Total ordering of proposals
  - Fault tolerance: proposal is accepted if a majority of acceptors accept it
  - There is always enough data available to recover the state of proposals
  - Is provably resilient in asynchronous networks
  - Paxos-based commit is a generalization of 2PC
    - Run a consensus algorithm on the commit/abort decision of EACH participant

Paxos for Commit Fault-tolerant Coordinator

The cast:
- One instance of Paxos per participant (N participants)
- Set of 2F+1 acceptors and a leader play the role of the coordinator
  - We can withstand the failure of F+1 acceptors
  - Leader = proposer elected to be in charge

Ready to start
Tell everyone
Each instance of Paxos proposes to commit or abort
Each instance of Paxos tells the result to the leader
A leader will get at least F+1 messages for each instance
Commit if every participant’s instance of Paxos chooses Prepared
Paxos commit = 2PC if one acceptor

Virtual Synchrony vs. Transactions vs. Paxos

- Virtual Synchrony
  - Fastest & most scalable
  - Focuses on group membership management & reliable multicasts
- Two-Phase & Three-Phase Commit
  - Most expensive – requires extensive use of stable storage
  - Designed for transactional activities
  - Not suitable for high speed messaging
- Paxos
  - Performance limited by its two-phase protocol
  - Great for consensus & fault tolerance
  - Adds ordering of proposals over 2PC
Scaling Transactions

- Transactions require locking part of the database so that everyone sees consistent data at all times
  - Good on a small scale.
  - Low transaction volumes: getting multiple databases consistent is easy
  - Difficult to do efficiently on a huge scale
- Add replication – processes can read any replica
  - All replicas must be locked during updates to ensure consistency
- Risks of not locking:
  - Users run the risk of seeing stale data
  - The “I” of ACID may be violated
  - E.g., two users might try to buy the last book on Amazon

Scaling also affects availability

- One database with 99.9% availability
  - 8 hours, 45 minutes, 35 seconds downtime per year
- If a transaction uses 2PC protocol and requires two databases, each with a 99.9% availability:
  - Total availability = (0.999*0.999) = 99.8%
  - 17 hours, 31 minutes, 12 seconds downtime per year
- If a transaction requires 5 databases:
  - Total availability = 99.5%
  - 1 day, 19 hours, 48 minutes, 0 seconds downtime per year

Delays hurt

- The delays to achieve consistency can hurt business
- Amazon:
  - 0.1 second increase in response time will cost them 1% of sales
- Google:
  - 0.5 second increase in latency causes traffic to drop by 20%
- Latency is due to lots of factors
  - OS & software architecture, computing hardware, tight vs loose coupling, network links, geographic distribution, …
  - We’re only looking at the problems caused by the tight software coupling due to achieving the ACID model

Eric Brewer’s CAP Theorem

- Three core requirements in a shared data system:
  1. Consistency
  2. Availability
  3. Partition Tolerance: tolerance to network partitioning
  - No set of failures less than total failure is allowed to cause the system to respond incorrectly
- CAP Theorem: you can only have at most two of these!

Example

Life is good

Network partition occurs

Do we want to give up consistency or availability?
Giving up one of \{C, A, P\}

- **Give up partitions** [partitions cannot occur]
  - Put everything on one machine or a cluster in one rack: high availability clustering
  - Use two-phase commit or three phase commit
  - Scaling suffers

- **Give up availability** [system is consistent & can handle partitioning]
  - Lock data: have services wait until data is consistent
  - Classic ACID distributed databases (also 2PC)
  - Response time suffers

- **Give up consistency** [system may not be consistent]
  - Eventually consistent data
  - Use expirations/leases, queued messages for updates
  - Examples: DNS, web caching, Amazon Dynamo, Hadoop HBase, CouchDB
  - Often not as bad as it sounds!

### BASE: an alternative to ACID

- Traditional database systems want ACID
  - But scalability is a problem
    - (lots of transactions in a distributed environment)

- Give up **Consistent and Isolated**
  - Get rid of locking in exchange for multiple versions
  - Incremental replication

- **BASE:**
  - Basically Available
  - Soft-state
  - Eventual Consistency

### ACID vs. BASE

**ACID**

- Strong consistency
- Isolation
- Focus on commit
- Nested transactions
- Availability is problematic
- Pessimistic access to data (locking)

**BASE**

- Weak (eventual) consistency: stale data at times
- High availability
- Best effort approach
- Optimistic access to data
- Simpler model (but harder for app developer)
- Faster

From Eric Brewer’s PODC Keynote, July 2000


### A place for BASE

- ACID is neither dead nor useless
  - Many environments require it

- BASE has become common for large-scale web apps
  - eBay, Twitter, Amazon
  - Eventually consistent model not always surprising to users
  - Cellphone usage data
  - Banking transactions (e.g., fund transfer activity showing up on statement)
  - Posting of frequent flyer miles

The End