Transactions & Two Phase Commit

CS 475, Fall 2019
Concurrent & Distributed Systems
Designing and Building Distributed Systems

To help design our algorithms and systems, we tend to leverage abstractions and models to make assumptions.

Generally: Stronger assumptions -> worse performance
Weaker assumptions -> more complicated

- **System model**: Synchronous → Asynchronous
- **Failure Model**: Byzantine → Crash-fail → Partitions
- **Consistency Model**: Sequential → Eventual
N-Tier Web Architectures

Real Architectures

Clients

Internet

External Cache

Web Servers

App Servers

Database servers

Internal Cache

Misc Services
Today

• First discussion of fault tolerance, in the context of transactions
• Agreement and transactions in distributed systems
boolean transferMoney(Person from, Person to, float amount) {
    if (from.balance >= amount) {
        from.balance = from.balance - amount;
        to.balance = to.balance + amount;
        return true;
    }
    return false;
}
Transactions: Classic Example

```java
boolean transferMoney(Person from, Person to, float amount){
    if(from.balance >= amount)
    {
        from.balance = from.balance - amount;
        to.balance = to.balance + amount;
        return true;
    }
    return false;
}
```

What’s wrong here?
Need isolation (prevent over-drawing)

1. `transferMoney(P1, P2, 100)`
   - P1.balance (200) >= 100
   - P1.balance = 200 - 100 = 100
   - P2.balance = 200 + 100 = 300
   - return true;

2. `transferMoney(P1, P2, 200)`
   - P1.balance (200) >= 200
   - P1.balance = 100 - 200 = -100
   - P2.balance = 300 + 200 = 500
   - return true;
Transactions: Classic Example

```java
boolean transferMoney(Person from, Person to, float amount)
{
    synchronized(from){
        if(from.balance >= amount)
        {
            from.balance = from.balance - amount;
            to.balance = to.balance + amount;
            return true;
        }
    }
    return false;
}
```

Adding a lock: prevents accounts from being overdrawn

```
transferMoney(P1, P2, 100)
P1.balance (200) >= 100
P1.balance = 200 - 100 = 100
P2.balance = 200 + 100 = 300
return true;
```

```
transferMoney(P1, P2, 200)
P1.balance < 200
return false;
```

But: shouldn’t we lock on to also?
Transactions: Classic Example

```java
boolean transferMoney(Person from, Person to, float amount) {
    synchronized(from){
        if(from.balance >= amount) {
            from.balance = from.balance - amount;
            to.balance = to.balance + amount;
            return true;
        }
        return false;
    }
    return false;
}
```

Transactions: Classic Example

- `transferMoney(P1, P2, 100)`
  - `P1.balance (200) >= 100`
  - `P1.balance = 200 - 100 = 100`
  - `P2.balance = 200 + 100 = 300`
  - `return true;`

- `transferMoney(P2, P1, 100)`
  - `P2.balance (200) >= 100`
  - `P2.balance = 200 - 100 = 100`
  - `P1.balance = 200 + 100 = 300`
  - `return true;`

Need to lock on both!
Transactions: Classic Example

```java
boolean transferMoney(Person from, Person to, float amount) {
    synchronized (from, to) {
        if (from.balance >= amount) {
            from.balance = from.balance - amount;
            to.balance = to.balance + amount;
            return true;
        }
        return false;
    }
    return false;
}
```

Transactions: Classic Example

`transferMoney(P1, P2, 100)`

- P1.balance (200) >= 100
- P1.balance = 200 - 100 = 100

`transferMoney(P1, P2, 200)`

- P1.balance < 200
- return false;

Problem: **P1.balance** was deducted **P2.balance** not incremented! ("Atomicity violation")
Transactions

• How can we provide some consistency guarantees across operations
• Transaction: unit of work (grouping) of operations
  • Begin transaction
  • Do stuff
  • Commit OR abort
• Why distributed transactions?
  • Data might be huge, spread across multiple machines
  • Scale performance up
  • Replicate data to tolerate failures
Properties of Transactions

• Traditional properties: ACID
  • Atomicity: transactions are “all or nothing”
  • Consistency: Guarantee some basic properties of data; each transaction leaves the database in a valid state
  • Isolation: Each transaction runs as if it is the only one; there is some valid serial ordering that represents what happens when transactions run concurrently
  • Durability: Once committed, updates cannot be lost despite failures
Concurrency control: Consistency & Isolation
2-phase locking

• Simple solution for isolation
• Phase 1: acquire locks (all that you might need)
• Phase 2: release locks
  • You can’t get any more locks after you release any
  • Typically: locks released when you say “commit” or “abort”
boolean transferMoney(Person from, Person to, float amount){
    from.lock();
    if(from.balance >= amount)
    {
        from.balance = from.balance - amount;
        from.unlock();
        to.lock();
        to.balance = to.balance + amount;
        to.unlock();
        return true;
    }
    else
    {
        from.unlock();
        return false;
    }
}

Invalid: other transactions could read an inconsistent system state at this point!
2-phase locking

```java
boolean transferMoney(Person from, Person to, float amount){
    from.lock();
    if(from.balance >= amount)
    {
        from.balance = from.balance - amount;
        to.lock();
        to.balance = to.balance + amount;
        to.unlock();
        from.unlock();
        return true;
    }
    else
    {
        from.unlock();
        return false;
    }
}
```

Might deadlock if one transaction gives from P1->P2, other P2->P1
Serializability

• Ideal isolation semantics
• Slightly stronger than sequential consistency
• Definition: execution of a set of transactions is equivalent to some serial order
  • Two executions are equivalent if they have the same effect on program state and produce the same output
  • Just like sequential consistency, but the outcome must be equivalent to an ordering where nothing happens concurrently, no re-ordering of events between multiple transactions.
2-Phase Locking Ensures Serializability of Transactions

- Allows serializability to be considered at the level of transactions, which might include multiple variables
- If a transaction $T$ accesses variables $A$ and $B$, and $T'$ accesses variables $A$ and $B$, then either:
2-Phase Locking Ensures Serializability of Transactions

- Allows serializability to be considered at the level of transactions, which might include multiple variables
- If a transaction $T$ accesses variables $A$ and $B$, and $T'$ accesses variables $A$ and $B$, then either:

```
<table>
<thead>
<tr>
<th></th>
<th>T'</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access</td>
<td>Access A</td>
<td>Access</td>
</tr>
<tr>
<td></td>
<td>Access B</td>
<td>A</td>
</tr>
</tbody>
</table>
```
Individual variable accesses are sequentially consistent, but transactions are not serializable!

If a transaction T accesses variables A and B, and T’ accesses variables A and B, then either:
Proof of Serializability - 2PL

• Proof by contradiction
• Is it possible for T -> T' and T' -> … -> T? (different order for A and B)
• What would have happened?
  • 1. T releases lock of A
  • 2. T’ acquires lock of A
  • 3. T’ releases lock of B
  • 4. T acquires lock of B
• Hence, 1->2, 3->4
• But, required by 2PL: 4->1, 2->3 (or vv)
• Putting this together would be: 4->1->2, 2->3->4 aka a contradiction
Transactions Might Effect Things You Don’t Lock

Transaction 1: Update employees, set salary = salary*1.1

Transaction 2: Hire Carol, Hire Mike
Transactions Might Effect Things You Don’t Lock

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Can run concurrently: no overlapping locks!
Transactions Might Effect Things You Don’t Lock

Transaction 1: Update employees, set salary = salary*1.1

Transaction 2: Hire Carol, Hire Mike

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<table>
<thead>
<tr>
<th>Employee</th>
<th>Salary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bob</td>
<td>100</td>
</tr>
<tr>
<td>Herbert</td>
<td>100</td>
</tr>
<tr>
<td>Larry</td>
<td>100</td>
</tr>
<tr>
<td>Jon</td>
<td>100</td>
</tr>
<tr>
<td>Carol</td>
<td>100</td>
</tr>
</tbody>
</table>
Transactions Might Effect Things You Don’t Lock

### Employee Salary

<table>
<thead>
<tr>
<th>Employee</th>
<th>Salary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bob</td>
<td>110</td>
</tr>
<tr>
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<td>110</td>
</tr>
<tr>
<td>Larry</td>
<td>110</td>
</tr>
<tr>
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Transaction 1: Update employees, set salary = salary*1.1

Transaction 2: Hire Carol, Hire Mike

**Can run concurrently: no overlapping locks!**
Transactions Might Effect Things You Don’t Lock

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<td>110</td>
</tr>
<tr>
<td>Carol</td>
<td>110</td>
</tr>
<tr>
<td>Mike</td>
<td>100</td>
</tr>
</tbody>
</table>

Transaction 1: Update employees, set salary = salary*1.1

Transaction 2: Hire Carol, Hire Mike

Solution to prevent this: Transaction 1 must always acquire some lock to prevent any other transaction from touching the data!

Or: ignore this problem and accept the consequences
No half measures: How do we ensure the entire transaction happens, or none? (Atomicity, Durability)

If the machine crashes, can it commit?
Fault Recovery

• How do we recover transaction state if we crash?
• Goal:
  • Committed transactions are not lost
  • Non-committed transactions either continue where they were or aborted
• Plan:
  • Consider local recovery
  • Then distributed issues
Write-ahead logging

• Maintain a complete log of all operations INDEPENDENT of the actual data they apply to
• E.g. Transaction boundaries and updates
• Transaction operations considered provisional until commit is logged to disk
• Log is authoritative and permanent
Distributing Transactions

- System model: data stored in multiple locations, multiple servers participating in a single transaction. One server pre-designated “coordinator”
- Failure model: messages can be delayed or lost, servers might crash, but have persistent storage to recover from
Distributed Transactions

• Coordinator: Begins a transaction
  • Assigns a unique transaction ID
  • Responsible for commit + abort
  • In principle, any client can be the coordinator, but all participants need to agree on who is the coordinator
• Participants: everyone else who has the data used in the transaction
Agreement

• In distributed systems, we have multiple nodes that need to all agree that some object has some state
• Examples:
  • The value of a shared variable
  • Who owns a lock
  • Whether or not to commit a transaction
Agreement Generally

• Most distributed systems problems can be reduced to this one:
  • Despite being separate nodes (with potentially different views of their data and the world)…
  • All nodes that store the same object O must apply all updates to that object in the same order (consistency)
  • All nodes involved in a transaction must either commit or abort their part of the transaction (atomicity)
• Easy?
  • … but nodes can restart, die or be arbitrarily slow
  • … and networks can be slow or unreliable too
Properties of Agreement

- 2 kinds of properties, just like for mutual exclusion:
- Safety (correctness)
  - All nodes agree on the same value (which was proposed by some node)
- Liveness (fault tolerance, availability)
  - If less than N nodes crash, the rest should still be OK
Distributed Transactions

transferMoney("from": Barney@Goliath National, "to": Mortimer@Duke&Duke, "amount"=$1)
Initially: Barney.balance= $10000, Mortimer.balance=$10000

What can we hope for if these two actions happen at once?

10,000 printed twice, or:
10,001 and 9,999
(Atomicity of the transfer)
Distributed Transactions

```python
transferMoney("from": Barney@Goliath National, 
    "to": Mortimer@ Duke&Duke, "amount"=$1)
Initially: Barney.balance= $10000, Mortimer.balance=$10000
```

- **transferMoney:**
  - add(Mortimer,1)
  - add(Barney,-1)

- **auditRecords:**
  - tmp1 = get(Mortimer)
  - tmp2 = get(Barney)
  - print tmp1, tmp2

...But why is this hard? What can go wrong?

- auditRecords is interleaved with transferMoney?
- Server or network failure on either end
- Mortimer or Barney’s account might not even exist
Distributed Transactions

• We can easily solve our transfer problem by making this two transactions!
• Client tells the transaction system when to start/end each transaction
• System arranges transactions to ensure our ACID properties
• Today’s focus: how do we build that transaction system?

```
transferMoney:
  begin_transaction()
  add(Mortimer,1)
  add(Barney,-1)
  end_transaction()

auditRecords:
  begin_transaction()
  tmp1 = get(Mortimer)
  tmp2 = get(Barney)
  print tmp1, tmp2
  end_transaction()
```
Distributed Transactions

- Will focus much more on how to abort - because more can go wrong:
  - Abort must undo any in-progress modifications
  - Voluntary abort - some client validation fails (e.g. bank account doesn’t exist)
  - Abort might come from failure (server or network crash)
  - System might deadlock and need to abort
- Two big components, just like non-distributed transactions:
  - Concurrency control (2 phase locking, just like non-distributed)
  - Atomic commit
2-Phase Commit

• Separate the commit into two steps:
  • 1: Voting
    • Each participant prepares to commit and votes of whether or not it can commit
  • 2: Committing
    • Once voting succeeds, every participant commits or aborts
• Assume that participants and coordinator communicate over RPC
2PC: Voting

• Coordinator asks each participant: can you commit for this transaction?
• Each participant prepares to commit BEFORE answering yes
  • e.g. save transaction to disk for later recovery
  • Can not abort after saying yes
• Outcome of transaction is unknown until the coordinator receives all votes and says “do abort” or “do commit”
2PC Event Sequence

Coordinator
Transaction state:
- prepared
- committed
- done

Participant
Local state:
- prepared
- uncertain
- committed

Can you commit?
- Yes
- OK, commit
- OK I committed
transferMoney("from": Barney@Goliath National, "to": Mortimer@ Duke&Duke, "amount"=$1)

Initially: Barney.balance= $10000, Mortimer.balance=$10000

Requirements:
1. Atomicity (transfer happens or doesn't)
2. Concurrency control (serializability)
2PC Example

For simplicity, let’s assume transfer is:

```c
int transfer(src, dst, amt) {
    transaction = begin();
    src.bal -= amt;
    dst.bal += amt;
    return transaction.commit();
}
```
2PC Example

Coordinator (client or 3rd party)

Participant Goliath National

Participant Duke & Duke

If we can commit, then lock our customer, vote “yes”

If everyone can commit, then outcome == commit, else abort

transaction .commit()

prepare

prepare

response_{GNB}

response_{D&D}

outcome

outcome
2PC Correctness (Safety)

- Remember the two kinds of properties we want to get:
  - Safety (correctness)
    - All nodes agree on the same value (which was proposed by some node)
  - Liveness (fault tolerance, availability)
    - If less than N nodes crash, the rest should still be OK
- As presented so far, 2PC guarantees safety, because no participant can proceed with the commit
Fault Recovery

• How do we recover transaction state if we crash?
• Goal:
  • Committed transactions are not lost
  • Non-committed transactions either continue where they were or aborted
• First: lay out various failure modes and discuss intuitions for solutions
  • Crashes for participant and coordinator; timeouts for same
• Then: formalize a policy for recovery in 2PC
Fault Recovery Example

Example: Participant crashes after voting “yes” to commit

Solution: Participants must keep track of transaction status on persistent storage for recovery on reboot
**Fault Recovery Example**

Example: Coordinator crashes after receiving votes

Solution: Coordinator must keep track of transaction status on persistent storage for recovery on reboot
Fault Recovery Example

Example: Coordinator times out waiting for a response

Solution: Coordinator can default to “abort” on timeout
Recovery in 2PC

• What to log?
  • State changes in protocol
  • Participants: prepared; uncertain; committed/aborted
  • Coordinator: prepared; committed/aborted; done
  • These messages are idempotent - can be repeated
• Recovery depends on failure
  • Crash + reboot + recover
  • Timeout + recover
Crash + Reboot Recovery

- Nodes can’t back out once commit is decided
- If coordinator crashes just AFTER deciding “commit”
  - Must remember this decision, replay
- If participant crashes after saying “yes, commit”
  - Must remember this decision, replay
- Hence, all nodes need to log their progress in the protocol
2PC Example with logging

Coordinator (client or 3rd party)

Participant Goliath National

Participant Duke & Duke

transaction
.commit()

prepare

prepare

response

response

response

response

outcome

outcome

outcome

Log!

Log!

Log!

Log!

If everyone can commit, then outcome == commit, else abort

If we can commit, then lock our customer, vote “yes”
Recovery on Reboot

- If coordinator finds no “commit” message on disk, abort
- If coordinator finds “commit” message, commit
- If participant finds no “yes, ok” message, abort
- If participant finds “yes, ok” message, then replay that message and continue protocol
Timeouts in 2PC

• Example:
  • Coordinator times out waiting for Goliath National Bank’s response
  • Bank times out waiting for coordinator’s outcome message

• Causes?
  • Network
  • Overloaded hosts
  • Both are very realistic…
Coordinator Timeouts

• If coordinator times out waiting to hear from a bank
  • Coordinator hasn’t sent any commit messages yet
  • Can safely abort - send abort message
  • Preserves correctness, sacrifices performance (maybe didn’t need to abort!)
• If either bank decided to commit, it’s fine - they will eventually abort
Handling Bank Timeouts

• What if the bank doesn’t hear back from coordinator?
• If bank voted “no”, it’s OK to abort
• If bank voted “yes”
  • It can’t decide to abort (maybe both banks voted “yes” and coordinator heard this)
  • It can’t decide to commit (maybe other bank voted yes)
• Does bank just wait for ever?
Handling Bank Timeouts

• Can resolve SOME timeout problems with guaranteed correctness in event bank voted “yes” to commit
• Bank asks other bank for status (if it heard from coordinator)
• If other bank heard “commit” or “abort” then do that
• If other bank didn’t hear
  • but other voted “no”: both banks abort
  • but other voted “yes”: no decision possible!
2PC Timeouts

- We can solve a lot (but not all of the cases) by having the participants talk to each other
- But, if coordinator fails, there are cases where everyone stalls until it recovers
- Can the coordinator fail? … yes
- We’ll come back to this “discuss amongst yourselves” kind of transactions next week
2PC Summary

- Guarantees safety, but not liveness - there are situations in which the protocol can stall indefinitely
- Recovery requires considerable logging
- Relatively few messages required though, for each transaction (low latency)
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