Distributed Algorithms

Distributed Transactions

Contents

Introduction

Example (Transfer money between two accounts)

- Withdraw 200€ from account 1
- Deposit 200€ to account 2

What happens if one of the operations is not performed?

Definition (Transaction)

The execution of a sequence of actions on a server that must be either entirely completed or aborted, independently of other transactions

Our goals:

- We want to allow the execution of concurrent transactions, yet to maintain consistency
- We want to deal with the failure of either the server or the client

ACID Properties

- Atomicity
  - Either all operations are completed or none of them is executed
- Consistency
  - Application invariants must hold before and after a transaction;
  - during the transaction, invariants may be violated but this is not visible outside
- Isolation (Serializability)
  - Execution of concurrent transactions should be equivalent (in effect) to a serialized execution
- Durability
  - Once a transaction commits, its effect are permanent

Transactional syntax

- Applications are coded in a stylized way:
  - begin transaction
  - perform a series of read, write operations
  - terminate by commit or abort

Example of transaction (sketch)

---

transaction T

$v_x \leftarrow \mathsf{read}(\text{"}x\text{"})$

$v_y \leftarrow \mathsf{read}(\text{"}y\text{"})$

$v_z \leftarrow v_x + v_y$

$\mathsf{write}(\text{"}z\text{"}, z)$

commit

Flat transactions

- Simplest, relatively easy to implement
- Their greatest strength (atomicity) is also their weakness (*lack of flexibility*)
- Technical issues:
  - How to maintain isolation
  - How to maintain atomicity + consistency

Nested transactions

- Constructed from a number of sub-transactions
- Sub-transactions may run in parallel or in sequence
- The subdivision is logical
- Flexibility
  - When a transaction fails, all its sub-transactions must fail too
  - When a sub-transaction fails:
    - The parent transaction could fail
    - Or, alternative actions could be taken
- Example next slide

Nested transactions

Example of nested transaction (sketch)

```
transaction "book travel"
    start transaction "book flight"
    start transaction "book hotel"
    start transaction "book car"
    if "book car" aborted then
        start transaction "book bus"
    if "book flight" and "book hotel" and ("book car" or "book bus")
      committed then
        commit
    else
        abort
```

Distributed transactions

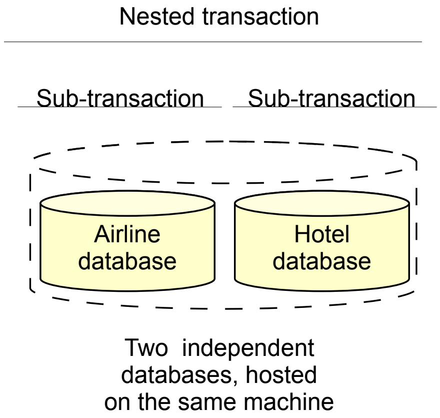
- Can be either flat or nested
- Operates on distributed data (multiple servers)
- Technical issues
  - Separate distributed algorithms are needed to handle
    - locking of data in multiple distributed systems
    - committing data in an atomic way

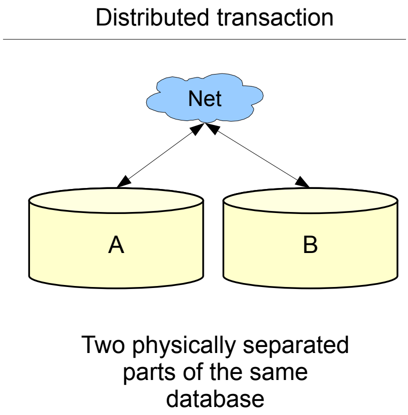
Distributed transactions

Example of distributed transaction (sketch)

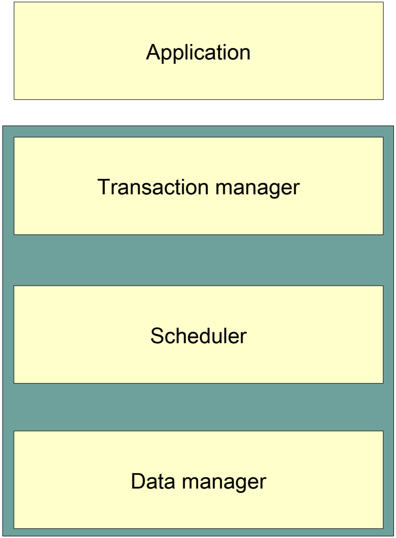
Site A, account x	Site B, account y
transaction T $v_x \leftarrow \mathsf{read}(''x'')$ $\mathsf{write}(''x'', v_x + C)$ **commit**	**transaction** T $v_y \leftarrow read(''y'')$ **if** $v_y \geq C$ **then** $\mathsf{write}(''y'', v_y - C)$ **commit** **abort**

Types of transactions





Transactional system



Application-specific code
(consistency)

Begin/commit/abort
(atomicity)

Lock management,
ordering of actions
(isolation)

Executes read/writes
(durability)

Atomicity

- Private workspaces
  - At the beginning, give the transaction a private workspace and copy all required objects
  - Read/write/perform operations on the private workspace
  - If all operations are successful, commit by writing the updates in the permanent record; otherwise abort
- How to extend this to a distributed system?
  - Each copy of the transaction on different server is given a private workspace
  - Perform a distributed atomic commitment protocol

Atomicity

- Write-ahead log
  - Write operation / initial state / final state on a log
  - Modify "real" data
- In case of commit
  - Mark operation as committed on the log
- In case of abort
  - Mark operation as aborted on the log
  - Revert "real" data to the initial state
- How to extend this to a distributed system?
  - Distributed rollback recovery

Atomicity

```
x = 0;
y = 0;
BEGIN_TRANSACTION;
   x = x + 1;
   y = y + 2;
   x = y * y;
END_TRANSACTION;
```

(a)

Log	Log	Log
[x = 0/1]	[x = 0/1]	[x = 0/1]
	[y = 0/2]	[y = 0/2]
		[x = 1/4]
(b)	(c)	(d)

Isolation

- Isolation
  - Means that effect of the interleaved execution is indistinguishable from some possible serial execution of the committed transactions
- Example:
  - T_1 and T_2 are interleaved but it "looks like" T_2 ran before T_1
- The idea:
  - Transactions can be coded to be correct if run in isolation, and yet will run correctly when executed concurrently (hence gain a speedup)

Isolation

- Alice withdraws 250€ from X
  1) $local \leftarrow \mathsf{read}(''x'')$
  2) $local \leftarrow local - 250$
  3) $\mathsf{write}(''x'', local)$
- Bob withdraws 250€ from X
  4) $local \leftarrow \mathsf{read}(''x'')$
  5) $local \leftarrow local - 250$
  6) $\mathsf{write}(''x'', local)$

What happens with the following sequences?

- 1-2-3-4-5-6 Correct
- 4-5-6-1-2-3 Correct
- 1-4-2-5-3-6 Lost update
- 1-2-4-5-6-3 Lost update

Isolation

T_1: $R_1(X)$ $R_1(Y)$ $W_1(X)$ $commit_1$

T_2: $R_2(X)$ $W_2(X)$ $W_2(Y)$ $commit_2$

DB: $R_1(X)$ $R_2(X)$ $W_2(X)$ $R_1(Y)$ $W_1(X)$ $W_2(Y)$ $commit_1$ $commit_2$

Isolation

T_1: $R_1(X)$ $R_1(Y)$ $W_1(X)$ $commit_1$

T_2: $R_2(X)$ $W_2(X)$ $W_2(Y)$ $commit_2$

DB: $R_1(X)$ $R_2(X)$ $\cancel{W_2(X)}$ $R_1(Y)$ $W_1(X)$ $W_2(Y)$ $commit_1$ $commit_2$

Unsafe! Not serializable

Problem: transactions may "interfere".

Here, T_2 changes x, hence T_1 should have either run first (read and write) or after (reading the changed value).

Isolation

T_1: $R_1(X)$ $R_1(Y)$ $W_1(X)$ $commit_1$

T_2: $R_2(X)$ $W_2(X)$ $W_2(Y)$ $commit_2$

DB: $R_2(X)$ $W_2(X)$ $R_1(X)$ $W_1(X)$ $W_2(Y)$ $R_1(Y)$ $commit_2$ $commit_1$

Data manager interleaves operations to improve concurrency but schedules them so that it looks as if one transaction ran at a time.

This schedule "looks" like T_2 ran first.

Locking

Unlike other kinds of distributed systems, transactional systems typically lock the data they access

- Lock coverage
  - suppose that transaction T will access object x
  - T must gets a lock that "covers" x
- We could have one lock
  - ...per object
  - ...for the whole database
  - ...for a category of objects
  - ...per table
  - ...per row
- All transactions must obey the same rules!

Strict 2-Phase locking (2-PL)

- 1^{st} phase (”growing”)
  - Whenever the scheduler receives an operation *operation*(T, x)
  - If x is already owned by a conflicting lock:
    - the operation (and the transaction) is delayed Otherwise:
    - the lock is granted
  - Obtain all the locks it needs while it runs and hold onto them even if no longer needed!
- 2^{nd} phase (”shrinking”)
  - release locks only after making commit/abort decision and only after updates are persistent

2-PL implies Serializability

- Suppose that T' performs an operation that conflicts with an operation that T has done
  - e.g., T' will update data item x that T read or updated
  - e.g., T updated item y and T' will read it
- T must have had a lock on x/y that conflicts with the lock that T' wants
  - T won't release it until it commits or aborts
  - So T' will wait until T commits or aborts
- Note: 2-PL may cause deadlocks; usual techniques apply

Durability: Lampson's stable storage

- Maintain two copies of object A (A_0 and A_1) plus two timestamps and checksums (different disks)
- Failure may happen at anytime between the six operations

Writing

$\textsc{update}(A, x)$

$A_0 \leftarrow x$
$T_0 \leftarrow \mathsf{now}()$
$S_0 \leftarrow \mathsf{checksum}(x, t_0)$
$A_1 \leftarrow x$
$T_1 \leftarrow \mathsf{now}()$
$S_1 \leftarrow \mathsf{checksum}(x, t_1)$

Recovery

$\textsc{read}(A)$

if $S_0 = \mathsf{checksum}(A_0, T_0) \wedge S_1 = \mathsf{checksum}(A_1, T_1)$ **then**
  if $T_0 > T_1$ **then** **return** A_0
  else **return** A_1
if $S_0 = \mathsf{checksum}(A_0, T_0) \wedge S_1 \neq \mathsf{checksum}(A_1, T_1)$ **then**
  return A_0
if $S_0 \neq \mathsf{checksum}(A_0, T_0) \wedge S_1 = \mathsf{checksum}(A_1, T_1)$ **then**
  return A_1

Distributed locking

- Centralized 2-PL
  - A single site is responsible for granting and releasing locks
  - Each scheduler communicates with this centralized scheduler
  - Issues: bottleneck, central point of failure
- Primary 2-PL
  - Each data item is assigned to a "primary" server
  - Each scheduler communicates with the scheduler of the primary
  - Issues: central points of failure
- Distributed 2-PL
  - Locking is done in a decentralized way; messages are exchanged through reliable multicast

Failures on centralized system

- If application crashes:
  - Treat as an abort
- If transactional system crashes:
  - Abort non-committed transactions, but committed state is durable
- Aborted transactions:
  - Leave no effect, either in database itself or in terms of indirect side-effects
  - Only need to consider committed operations in determining serializability

Distributed commit problem

- Atomic commitment
- The distributed commit problem involves having an operation being performed by a distributed set of participants
- Two protocols
  - Two-phase commit (2PC)
    - blocking, efficient
    - Jim Gray (1978)
  - Three-phase commit (3PC)
    - non-blocking
    - Dale Skeen (1981)
- Implementations based on a coordinator

System model

- Fixed set of participants, known to all
- No message losses
- Synchronous communication: all messages arrive in δ time units
- Δ_b-timeliness: it is possible to build a broadcast primitive such that all messages arrive in Δ_b time units
- Clocks exists
  - they are not required to be synchronized
  - they may drift from real-time

- Which systems:
  - local area networks

Generic Participant

Executed by the invoker
send $\langle$TSTART, *transaction*, *participants*$\rangle$ **to** *participants*

Executed by all participants (including the invoker)

upon receipt of $\langle$TSTART, *transaction*, *participants*$\rangle$ **do**
    $C_{know} \leftarrow \mathsf{now}()$
    { Perform operations requested by *transaction* }
    if willing and able to make updates permanent **then**
        vote = YES
    else
        vote = NO
    $\mathsf{AtomicCommitment}(transaction, participants)$

Coordinator selection

Coordinator axioms

- AX1 At most one participant will assume the role of coordinator
- AX2 If no failures occur, one participant will assume the role of coordinator
- AX3 There exists a known constant Δ_c such that no participant assumes the role of coordinator more than Δ_c time units after the beginning of the transaction

Specification

Atomic commitment

- **AC1** All participants that decide reach the same decision
- **AC2** If any participant decides commit, then all participants must have voted yes
- **AC3** If all participants vote yes and no failures occur, then all participants decide commit
- **AC4** Each participant decides at most once

Atomic commitment

A generic algorithm – *Atomic Commitment Protocol* (ACP)

- Based on a generic broadcast primitive
- By "plugging in" different versions of broadcast we obtain different versions of ACP

Three phases:

- **Phase 1**: The coordinator asks for votes yes/no from participants and take a commit/abort decision
- **Phase 2**: The coordinator disseminates the decision
- **Phase 3**: Termination protocol; we'll see

Atomic Commitment Protocol

```
procedure atomic_commitment(transaction, participants)
    cobegin
    % Task 1: Executed by the coordinator
        send [VOTE_REQUEST] to all participants
        set-timeout-to local_clock + 2δ
        wait-for (receipt of [VOTE: vote] messages from all
            if (all votes are YES) then
                broadcast (COMMIT, participants)
            else broadcast (ABORT, participants)
        on-timeout
            broadcast (ABORT, participants)
```

Atomic Commitment Protocol

% Task 2: Executed by all participants (including the coordinator)
set-timeout-to $C_{know} + \Delta_c + \delta$
wait-for (receipt of [VOTE_REQUEST] from coordinator)
send [VOTE: vote] **to** coordinator
if (vote = NO) **then**
decide ABORT
else
set-timeout-to $C_{know} + \Delta_c + 2\delta + \Delta_b$
wait-for (delivery of decision message)
if (decision message is ABORT) **then**
decide ABORT
else decide COMMIT
on-timeout
decide according to termination_protocol()
on-timeout
decide ABORT
coend
end

Terminating Best-Effort Broadcast

Definition (TBEB1 - Validity)

If p and q are correct, then every message B-broadcast by p is eventually delivered by q

Definition (TBEB2 - Uniform Integrity)

m is delivered by a process at most once, and only if it was previously broadcast

Definition (TBEB3 - Δ_b-Timeliness)

All messages arrive in Δ_b time units since the time they were sent

ACP - TBEB

- The ACP algorithm with a best-effort broadcast implementation
- It happens to be equivalent to 2PC

AC1: All participants that decide reach the same decision	See next page (too complex to fit in this box!)
AC2: If any participant decides **commit**, then all participants must have voted YES	From the structure of the program (the coordinator must have received yes from all participants)
AC3: If all participants vote YES and no failures occur, then all participants decide **commit**	Given reliable communication, no failure, synchrony, all messages arrives before deadlines
AC4: Each participant decides at most once	From the algorithm structure (decide op. are mutually exclusive)

Proof of AC1, by contradiction

1. Let p decide commit, let q decide **abort**. By AC4, $p \neq q$
2. p must have received a broadcast from a coordinator c
   2.1 By AC2, c must have received votes YES from all, including q
3. A process decide **abort** in lines 14,19, 24
   3.1 Line 14 is excluded by 2.1
   3.2 Line 24 is excluded by 2.
4. So q must have delivered a message **abort** in line 19
5. But this message must have been sent by a coordinator different from c; but this is a contradiction with AX1 (unique coordinator)

Blocking vs non-blocking

- In some cases, a termination protocol is invoked
- Informally, tries to contact other participants to learn a decision
  - For example:
    - if a process has already decided, copy the decision
    - if a process has not voted, decide **abort**
- But consider this scenario:
  - the coordinator crashes during the broadcast of a decision
  - all faulty participants decide and then crash
  - all correct participants have previously voted YES, and they do not deliver a decision
- ACP-TBEB is blocking in this scenario

Blocking vs non-blocking

Non-blocking atomic commitment

{ AC1–AC4 }

AC5 Every correct participant that executes the atomic commitment protocol eventually decides

Uniform Terminating Reliable Broadcast

Definition (URB1 - Validity)

If p and q are correct, then every message B-broadcast by p is eventually delivered by q

Definition (URB2 - Uniform Agreement)

If a ~~correct~~ process delivers m, then all correct processes eventually deliver m

Definition (URB3 - Uniform Integrity)

m is delivered by a process at most once, and only if it was previously broadcast

Definition (URB4 - Δ_b-Timeliness)

All messages arrive in Δ_b time units since the time they were sent

ACP - UTRB

```
% Task 2: Executed by all participants (including the coordinator)
    set-timeout-to $C_{know} + \Delta_c + \delta$
    wait-for (receipt of [VOTE_REQUEST] from coordinator)
        send [VOTE: vote] to coordinator
        if (vote = NO) then
            decide ABORT
        else
            set-timeout-to $C_{know} + \Delta_c + 2\delta + \Delta_b$
            wait-for (delivery of decision message)
                if (decision message is ABORT) then
                    decide ABORT
                else decide COMMIT
            on-timeout
                decide ABORT
    on-timeout
        decide ABORT
coend
```

ACP - UTRB

ACP - UTRB

If we use UTRB instead of TBEB, we obtain ACP-UTRB, which is equivalent to 3PC.

Correctness

The termination protocol is not needed any more.

Proof:

- AC1-AC4: only AC1 is changed from before, we need to prove that q cannot decide **abort** in line 22
- AC5: By the structure of the protocol, each line we have a decide

ACP - UTRB – Performance

- ACP- BEB
  - $4n$ total messages
  - n invoker-to-all
  - n coordinator-to-all
  - n all-to-coordinator
  - n coordinator-to-all
- ACP-UTRB
  - $3n + n^2$ total messages
  - n invoker-to-all
  - n coordinator-to-all
  - n all-to-coordinator
  - n^2 all-to-all

Recovery

- To conclude, we need to consider the possibility of a participant that was down becoming operational after being repaired

Recovery protocol

- During normal execution, log all "transactional events" in a distributed transaction log (dt-log)
  - T-START, VOTE YES, VOTE NO, **commit**, **abort**
- At recovery, try to conclude all transactions that were in progress at the participant at the time of crash
- If recovery is not possible by simply looking at the log, try to get help from other participants

Recovery protocol

```
procedure recovery_protocol(p)
% Executed by recovering participant p
    R := set of DT-log records regarding transaction
    case R of
        {}:                          skip
        {start}:                     decide ABORT
        {start,no}:                  decide ABORT
        {start,vote,decision}:       skip
        {start,yes}:
            while (undecided) do
                send [HELP, transaction] to all participants
                set-timeout-to 2δ
                wait-for receipt of [REPLY: transaction, reply] message
                    if (reply ≠?) then
                        decide reply
                    else
                        if (received ? replies from all participants) then
                            decide ABORT
                on-timeout
                    skip
```

Recovery protocol

```
upon (receipt of [HELP, transaction] message from p)
    R := set of DT-log records regarding transaction
    case R of
        {}:                         decide ABORT; send [REPLY: transaction, ABORT] to p
        {start}:                    decide ABORT; send [REPLY: transaction, ABORT] to p
        {start,no}:                 send [REPLY: transaction, ABORT] to p
        {start,vote,decision}:      send [REPLY: transaction, decision] to p
        {start,yes}:                send [REPLY: transaction, ?] to p
    esac
```

Reading Material

- O. Babaoglu and S. Toueg. Understanding non-blocking atomic commitment. In S. Mullender, editor, *Distributed Systems (2^{nd} ed.)*. Addison-Wesley, 1993. http://www.disi.unitn.it/~montreso/ds/papers/AtomicCommitment.pdf