Formal Verification of COCO Database Framework Using CSP

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Outline

- Introduction
- Overview of COCO Database
- Modeling COCO Database
- Verification
- Conclusion

Outline

Introduction

Background

- Many distributed OLTP databases use a shared-nothing architecture for scale out and data partitioning to achieve the scalability of data storage.
- Lu et al. proposed epoch-based commit and replication, which is an improved protocol based on 2PC, and implemented it in distributed database COCO.
- The COCO database also supports two variants of optimistic concurrency control: physical time and logical time OCC.

Motivation

- The design of a distributed database architecture often needs to satisfy many functional properties.
- For the reason that the test workload and benchmarks are artificially set, and the test results are directly affected by the hardware performance, the test results still can be improved.

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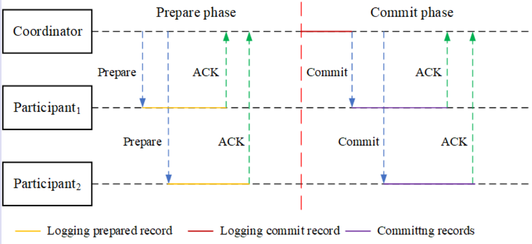
Overview of COCO Database

Overview of Epoch-based Commit Protocol and Replication



- The protocol commits transactions within the epoch synchronously at the end of the epoch.
- Epoch-based commit contains a *prepare* phase and a *commit* phase.
- COCO performs the replication on backup databases asynchronously.

Overview of COCO Database

Pseudo Code of Physical Time OCC

Algorithm 1 PT-OCC

Phase 1: Locking the write set

```
for record in T.WS do
    ok,tid=call_n(lock,record.key)
    if record not in T.RS then
        record.tid=tid
    end if
    if ok==false or tid!=record.tid then
        abort=true
    end if
end for
```

Phase 2: Validating the read set

```
for record in T.RS
T.WS do
    locked,tid=call_n(read_metadata,record.key)
    if locked or tid!=record.tid then
        abort=true
    end if
end for
```

Phase 3: Writing back to the database

```
for record in T.WS do
    call_n(db_write,record.key,record.value,record.tid)
    call_n(unlock, record.key)
    for i in get_replica_nodes(record.key) do
        call_i(db_replicate,record.key,record.value,T.tid)
    end for
end for
```

Overview of COCO Database

Pseudo Code of Logical Time OCC

Algorithm 2 LT-OCC

```
Phase 1: Locking the write set
for record in T.WS do
    ok,{wts,rts}=call_n(lock, record.key)
    if record not in T.RS then
        record.wts=wts
    end if
    if ok==false or wts!=record.wts then
        abort()
    end if
    record.rts=rts
end for
Phase 2: Validating the read set
for record in T.RS
T.WS do
    if record.rts<T.tid then
        locked,{wts,rts}=call_n(read_matadata,record.key)
    end if
    if wts!=record.wts or (rts<T.tid and locked) then
        abort()
    end if
    call_n(write_metadata,record.key,locked,{wts,T.tid})
end for
Phase 3: Writing back to the database
for record in T.WS do
    wts,rts=T.tid,T.tid
    call_n(db_write,record.key,record.value,{wts,rts})
    call_n(unlock, record.key)
    for i in get_replica_nodes(record.key) do
        call_i(db_replicate,record.key,record.value,{wts,rts})
    end for
end for
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Modeling COCO Database

- COCO architecture includes epoch-based commit protocol, replication protocol and two variants of optimistic concurrency control.

Overview the Model

$$Epoch\_commit() =_{df} Coordinator() || (|||i : \{1...N\} @ Participant(i))$$

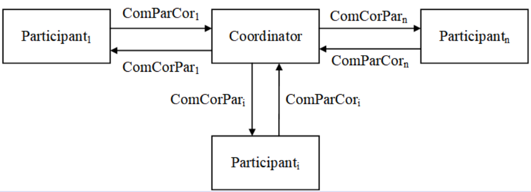
$$Replication(records) =_{df}$$
$$Primary\_replication(records) || (|||i : \{1...N\} @ Replica(i)))$$

$$PT\_OCC() =_{df}$$
$$(|||i : \{1...N\} @ Transaction\_PT(i, read\_set_i, write\_set_i))$$
$$|| Primary() || (|||i : \{1...N\} @ Replica(i))$$

$$LT\_OCC() =_{df}$$
$$(|||i : \{1...N\} @ Transaction\_LT(i, read\_set_i, write\_set_i))$$
$$|| Primary() || (|||i : \{1...N\} @ Replica(i))$$

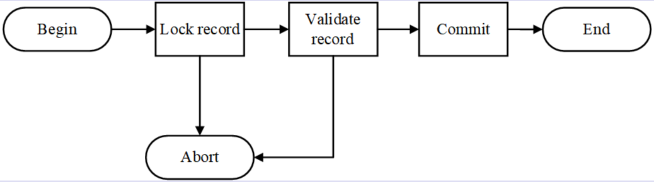
Overview of COCO Database

Overview of Epoch-based Commit Protocol and Replication



- The protocol commits transactions within the epoch synchronously at the end of the epoch.
- Epoch-based commit contains a *prepare* phase and a *commit* phase.
- COCO performs the replication on backup databases asynchronously.

Overview of PT-OCC and LT-OCC



- These algorithms can be divided into three phases: locking, validating and commit.
- In locking phase, transactions lock all data records they need to operate. If transaction can't lock all records it needs, it simply aborts.
- In validating phase, transactions validate records they locked with their read sets. If versions of these records are inconsistent, transaction simply aborts.
- In commit phase, transactions commit their write sets.

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Verification

- In COCO, we should avoid the situation that two or more clients are waiting the resources which have been occupied by other clients infinitely.
- In the tool PAT, there is a primitive to describe this situation.

Property 1: Deadlock Freedom

$\#$*assert System*() *deadlockfree*;

Verification

- This property asserts during the execution of a transaction, data can only be converted from one consistency state to another consistency state.

Property 2: Consistency

$\#define\ Consistency\ (\wedge i : \{1...N\} record_i == last\_rec$
$ord) \vee (\wedge i : \{1...N\} record_i == cur\_record)$
$\#assert\ Epoch\_commitI() \mid = \ Consistency$

Verification

- It means every request in a distributed system can be responded to.

Property 3: Availability

$\#define\ Availability\ (hasNo == True \land finished == True)$
$\#assert\ Epoch\_commit() \mid= \ Availability$

- It means that when a node or network partition in a distributed system fails, the entire system can still provide external services that satisfy consistency and availability.

Property 4: Partition Tolerance

$\#define\ PartitionTolerance\ finished == True$
$\#assert\ Epoch\_commit() \mid= PartitionTolerance$

Verification

- This property means that when some requests failure or unpredictable failures occur in the system, the system can still guarantee the normal execution of most transactions.

Property 5: Basically Availability

$\#define\ BasicallyAvailability\ (existCrash == True) \wedge$
$(available == True)$
$\#assert\ PT\_OCC()\ |=\ BasicallyAvailability$
$\#assert\ LT\_OCC()\ |=\ BasicallyAvailability$

Verification

- It refers to the fact that all data copies in the system can finally reach a consistent state after a period of synchronization without the guarantee of strong consistency of system data.

Property 6: Eventually Consistency

$\#define\ EventuallyConsistency\ EG((\wedge i:\{1...N\}recor$
$d_i == last\_record) \vee (\wedge i:\{1...N\}record_i == cur\_record))$
$\#assert\ PT\_OCC() \mid= \ BasicallyAvailability$
$\#assert\ LT\_OCC() \mid= \ BasicallyAvailability$

Verification

- This property refers to allowing the data in the system to have an intermediate state, and this state does not affect the overall availability of the system.

Property 7: Soft State

$\#define\ SoftState\ (\vee i : \{1...N\} record_i! = last\_rec$
$ord) \wedge (\vee i : \{1...N\} record_i! = cur\_record)$
$\#assert\ PT\_OCC() \mid = \ SoftState$
$\#assert\ LT\_OCC() \mid = \ SoftState$

Verification

Evaluation Result

We use the model checker PAT to verify the main frameworks of COCO distributed database such as epoch-based commit and replication, PT-OCC and LT-OCC. The verification results are shown below.

✓	1	CommitProtocol() deadlockfree
✓	2	CommitProtocol() |= Consistency
✓	3	CommitProtocol() reaches Availability
✗	4	CommitProtocol() reaches PartitionTolerance
✓	5	PT_OCC() deadlockfree
✓	6	PT_OCC_BA() reaches BasicallyAvailability
✓	7	PT_OCC_EC() reaches SoftState
✓	8	PT_OCC_EC() |= F G EventuallyConsistency
✓	9	LT_OCC() deadlockfree
✓	10	LT_OCC_BA() reaches BasicallyAvailability
✓	11	LT_OCC_EC() reaches SoftState
✓	12	LT_OCC_EC() |= F G EventuallyConsistency

Outline

Conclusion

- Conclusion
  - The CAP and BASE theories put forward the properties that the distributed system architecture needs to satisfy, and we verified the properties of COCO in an epoch cycle.
  - It has been verified that (1) epoch-based commit and replication satisfy consistency and availability but not partition tolerance, and (2) PT-OCC and LT-OCC satisfy basic availability, soft state, and eventually consistency.
  - This shows that COCO can guarantee high availability during an epoch cycle, and can also guarantee consistency at the end of the epoch.
- Future Work
  - In the future, we will verify the isolation of COCO and sequential consistency of concurrency control.

Thank you