IPADS INSTITUTE OF PARALLEL AND DISTRIBUTED SYSTEMS

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

OCC, MVCC & Multi-site atomicity

IPADS, Shanghai Jiao Tong University

https://www.sjtu.edu.cn

Optimistic concurrency control (OCC)

Problem of 2PL for before-or-after: locking overhead + deadlock

- Pessimistically execute the TX to avoid race conditions

Executing TXs optimistically w/o acquiring the lock

- Checks the results of TX before it commits
- If violate serializability, then **aborts & retries**

First proposed in 1981, widely used today (even in hardware impl. !)

Review: Optimistic Concurrency Control

Phase 1: Concurrent local processing

- Reads data into a read set
- Buffers writes into a write set

Phase 2: Validation serializability in critical section

- Validates whether serializability is guaranteed:
- Has any data in the read set been modified?

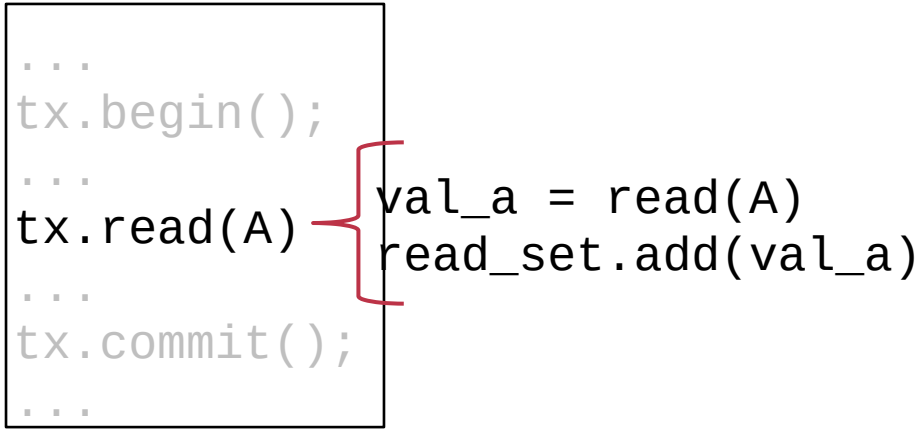
Phase 3: Commit the results in critical section or abort

- Aborts: aborts the transaction if validation fails
- Commits: installs the write set and commits the transaction

Review: OCC Executes a Transaction in 3 Phases

Phase 1:

- Reads data into a read set
- Buffers writes into a write set



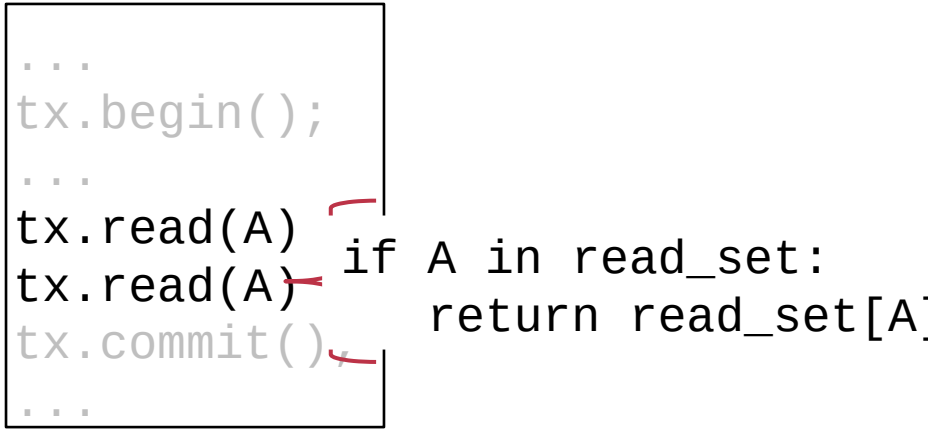
Review: OCC Executes a Transaction in 3 Phases

Phase 1:

- Reads data into a read set
- Buffers writes into a write set

What about a second read?

- Read from the read-set!
- Why? Need to provided repeated read!



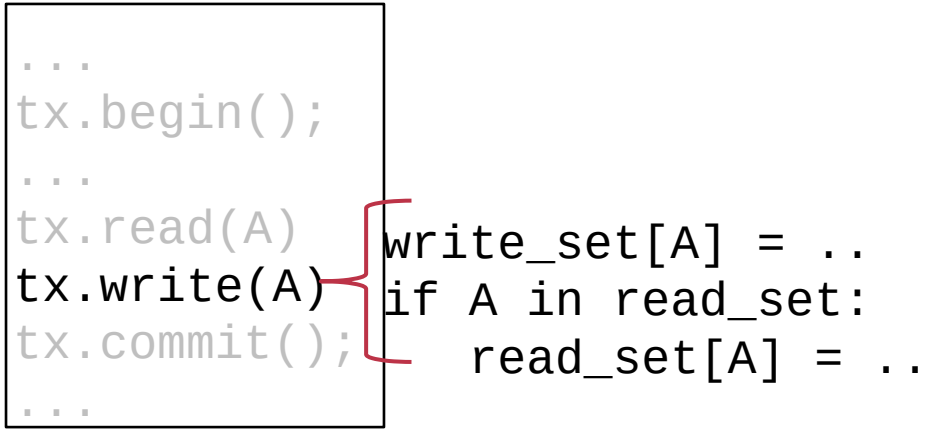
Review: OCC Executes a Transaction in 3 Phases

Phase 1:

- Reads data into a read set
- Buffers writes into a write set

Question

- Why do we need to update the readset? Is It necessary?



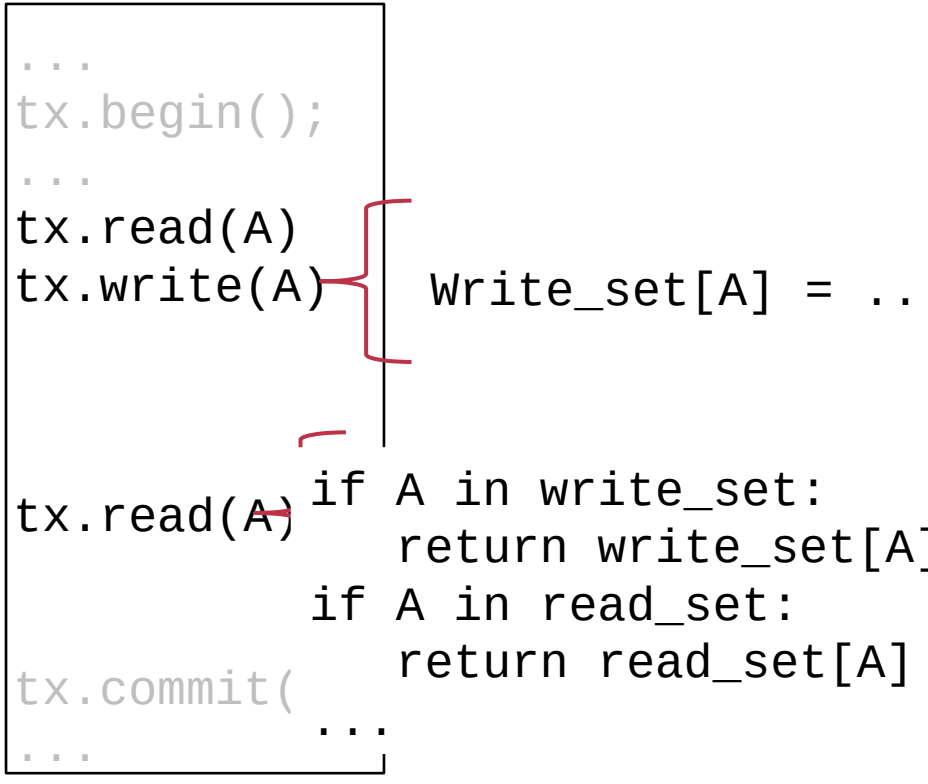
Review: OCC Executes a Transaction in 3 Phases

Phase 1:

- Reads data into a read set
- Buffers writes into a write set

Question

- Why do we need to update the readset? Is It necessary?
- Goal: we need to ensure later read will see my write
- We can avoid updating the readset by checking the writeset during reads



Review: OCC Executes a Transaction in 3 Phases

Phase 2:

- Validates whether serializability is guaranteed:
- Has any data in the read set been modified?

```
...
tx.begin();
...
tx.read(A)
...
tx.commit();
...
```

```
for d in read_set:
    if d has changed:
        abort()
```

Review: OCC Executes a Transaction in 3 Phases

Phase 3:

- Aborts: aborts the transaction if validation fails
- Commits: installs the write set and commits the transaction

```
...
tx.begin();
...
tx.read(A)
...
tx.commit();
...
```

```
for d in read-set:
   if d has changed:
      abort()
for d in write_set:
   write(d)
```

OCC Executes a Transaction in 3 Phases

Phase 3:

- Aborts: aborts the transaction if validation fails
- Commits: installs the write set and commits the transaction

Phase 2 & 3 should execute in a critical section

- Otherwise, what if a value has changed during validation?

```
...
tx.begin();
...
tx.read(A)
...
tx.commit();
...
```

Critical section

```
for d in read_set:
   if d has changed:
      abort()
for d in write_set:
   write(d)
```

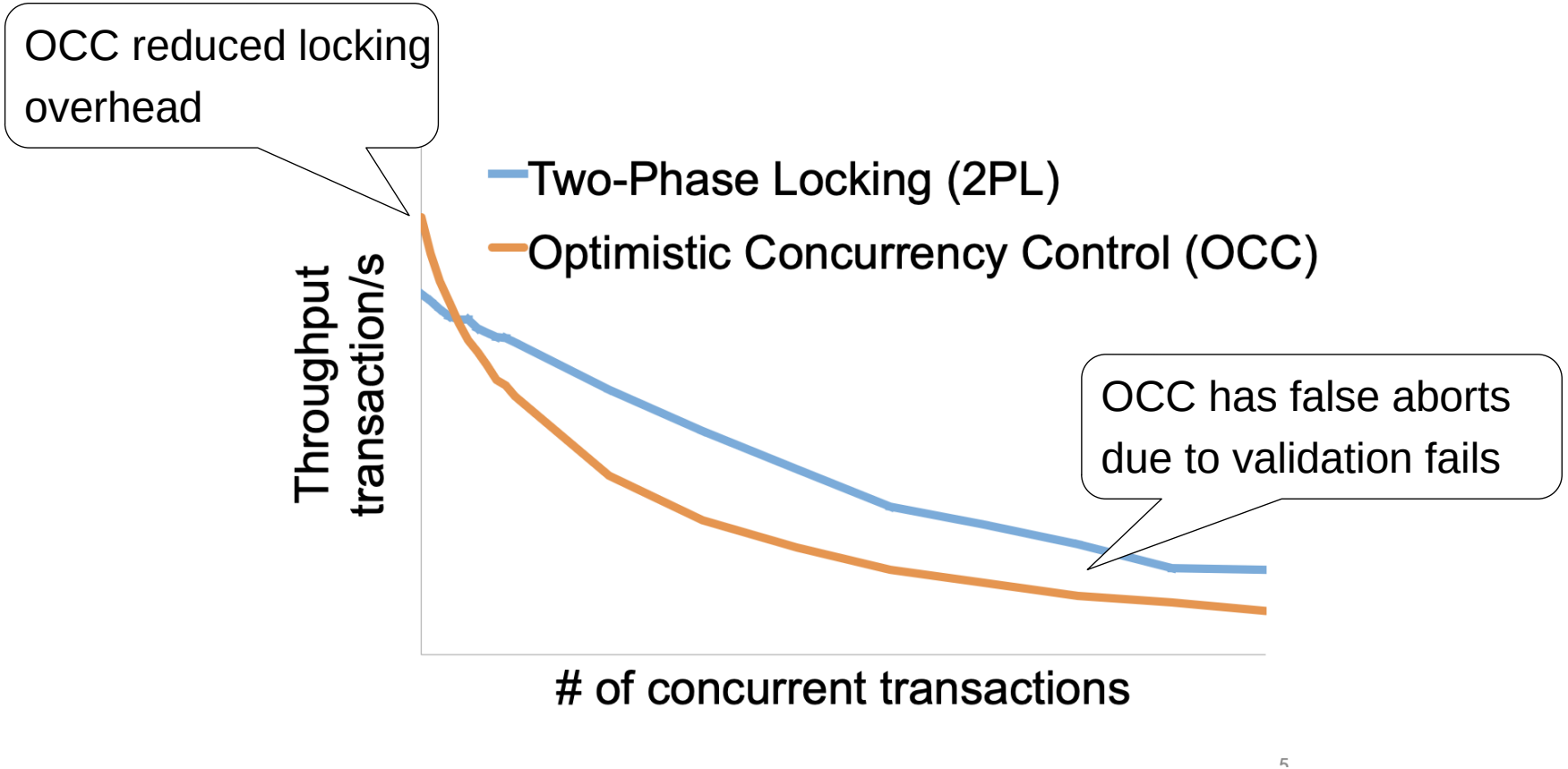
How to implement the critical section for phase 2 & 3?

Use two-phase locking + read validation

- Only lock the write set, after that,
- Check the read set has not changed & locked

```
def validate_and_commit() // phase 2 & 3 with before-or-
after
    for d in sorted(write-set):
        d.lock()
    for d in read-set:
        if d has changed or d has been locked:
           abort()
    for d in write-set:
        write(d)
    // release the locks
    ...
```

2PL vs. OCC: in a nutshell



Source: Extracting More Concurrency from Distributed Transactions [OSDI'14]

OCC & hardware transactional memory

Hardware Transactional Memory

A CPU feature for writing concurrent programs

CPU guarantees the before-or-after atomicity of memory reads/writes

- i.e., no race conditions & no need for 2PL & (Software-implemented) OCC!

Intel's HTM named as RTM

- Restricted Transactional Memory
- First released in Haswell processor

Other implementations also exist

- E.g., ARM Transactional Memory Extension (TME)

Let’s look at how to use HTM (RTM)

ISA support for transactional memory

- The ISA is very similar to what we have been described for TXs

Recall: Writing with TX in software

- Use `TX.begin` to mark when a TX starts
- Use `TX.commit` to commit the TX

In RTM, the concept is similar (new assemble code)

- Use `xbegin` to mark an RTM execution start
- Use `xend` to mark an RTM end

Programming with RTM

If transaction starts successfully

- Do work protected by RTM, and then try to commit

CPU detects race condition & aborts if necessary

- If abort, CPU rollbacks to line xbegin, return an abort code

Manually abort inside a transaction

```
if _xbegin() ==
_XBEGIN_STARTED:
    if conditions:
      _xabort()
   critical code
    _xend()
else
   fallback routine
```

Programming with RTM

If transaction starts successfully

- Do work protected by RTM, and then try to commit

CPU detects race condition & aborts if necessary

- If abort, CPU rollbacks to line `xbegin`, return an abort code

Manually abort inside a transaction

```
if _xbegin() ==
_XBEGIN_STARTED:
    if conditions:
      _xabort()
   critical code (access x)
     _xend()
else
   abort case
```

Another process

```
x = 1
```

Programming with RTM

If transaction starts successfully

- Do work protected by RTM, and then try to commit

CPU detects race condition & aborts if necessary

- If abort, CPU rollbacks to line `xbegin`, return an abort code

Manually abort inside a transaction

```
if _xbegin() ==
_XBEGIN_STARTED:
    if conditions:
     _xabort()
   critical code
    _xend()
else
   abort case
```

RTM: pros & cons

The benefits of RTM

- Memory operations between `xbegin() & xend()`satisfy before-of-after
- Much easier to program than 2PL or OCC (in most cases)
- In some cases, the performance is better

```
extern std::vector<u64> data; // shared by multiple threads
if _(xbegin() == _XBEGIN_STARTED)
      data.push(12);
else
      ?
```

Drawbacks

- Cannot guarantee success

Problem: RTM cannot guarantee success

No guaranteed success. So handling the abort case is more complex

- E.g., we cannot use a simple retry-base strategy
- Otherwise, we may encounter livelock

Why RTM cannot guarantee success?

```
Beginning:
        if _xbegin() == _XBEGIN_STARTED
            /* do some critical work */
            _xend()
        else
            goto beginning
```

Simply Retry

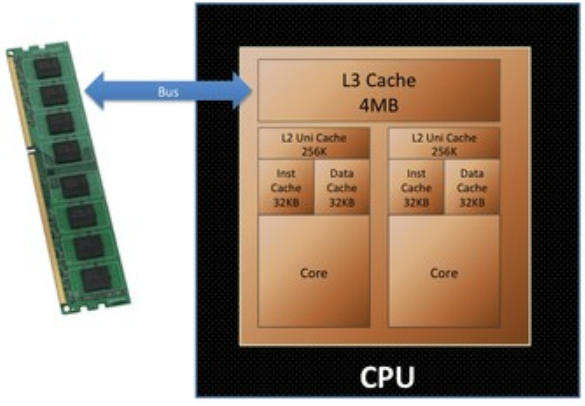
Fun facts about the implementation of RTM

Intel implements RTM using optimistic concurrency control

- OCC itself does not guarantee success

RTM's OCC is implemented on the CPU hardware, which has restrictions

- Use CPU cache to track the **read/write sets of CPU reads/writes**
- Use **cache coherence** protocols to detect conflicts



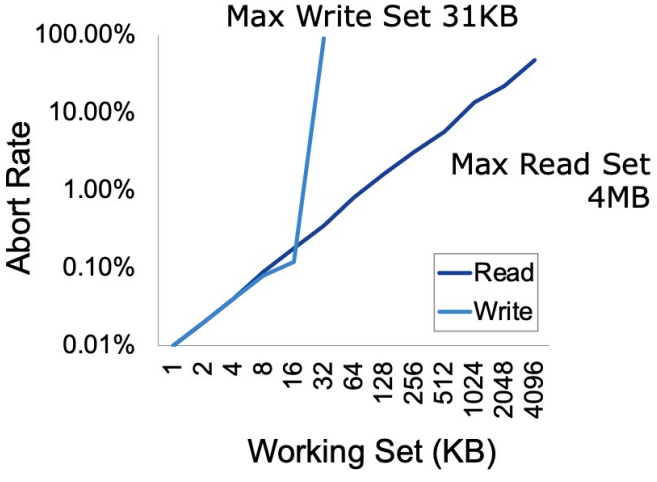
RTM: limited working set

CPU has limited cache capacity

- If the read/write sets exceed the cache size, the RTM will unconditionally abort

How big is the RTM read/write sets?

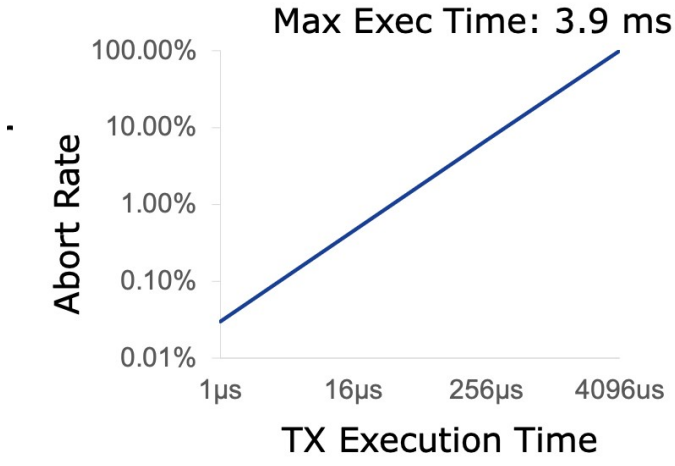
- Depends on various factors
  - Hardware setup (e.g., CPU cache size)
  - Access pattern: read or write
  - L1 cache tracks all the writes
  - L2 or L3 to tracks all the reads
  - Why not using L2 or L3 to track reads/writes?



RTM: limited execution time

The longer the execution, the higher the probability a TX aborts

- Root cause: CPU interrupts will also unconditionally abort the TX
- Why will interrupt cause an RTM to abort? Context switch will pollute the cache



Fallback path: make RTM finally commits

Problem: RTM cannot guarantee success

- Similar to OCC, code in RTM can be frequently aborted due to conflicts
- It can also be aborted due to hardware restrictions described above

Must switch to a fallback path after *some* retries (e.g., using a counter)

- E.g., fallback to locking; if fallbacks frequently, no performance benefits

```
if _xbegin() == _XBEGIN_STARTED
    if lock.held()
        xabort()
      /* do some critical work */
    _xend()
else
    lock.acquire()
```

check lock status to avoid conflict with fallback handlers on other CPU

Switch to Pessimistic Sync.

HTM on transactions

Naïve: using HTM to execute the in-memory transaction

- Smallbank: transfer &. Audit
- TPC-C: much complex, insert 10+ orders and update 10+ stocks

Silo@SOSP’13: the fastest in-memory OCC implementation

Short summary of OCC & RTM

OCC is yet another classic protocol for before-or-after atomicity

- Whose idea has even been adopted by hardware designers

Hardware support for transactional memory

- Easy programming model for the programmer (no need for locking)
  - As long as the programmer do the in-memory computations, e.g., in-memory database
- Good performance if using properly
  - No need for locking & atomic operations
- However, the programmer should handle its pitfalls

OCC & 2PL are bad when TXs are long running w/ many reads

OCC: abort due to read validation fails

2PL: read will hold the lock and block others

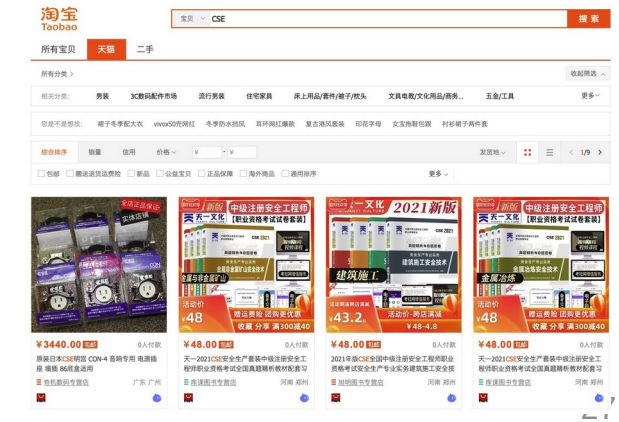
Yet, reads are common in applications

e.g., for Taobao, we rarely add items, but extensively read the items

- Scenario: long-running read-only or read-mostly transactions

run analytics on a companion data, while update a piece of data

long running read-only transaction

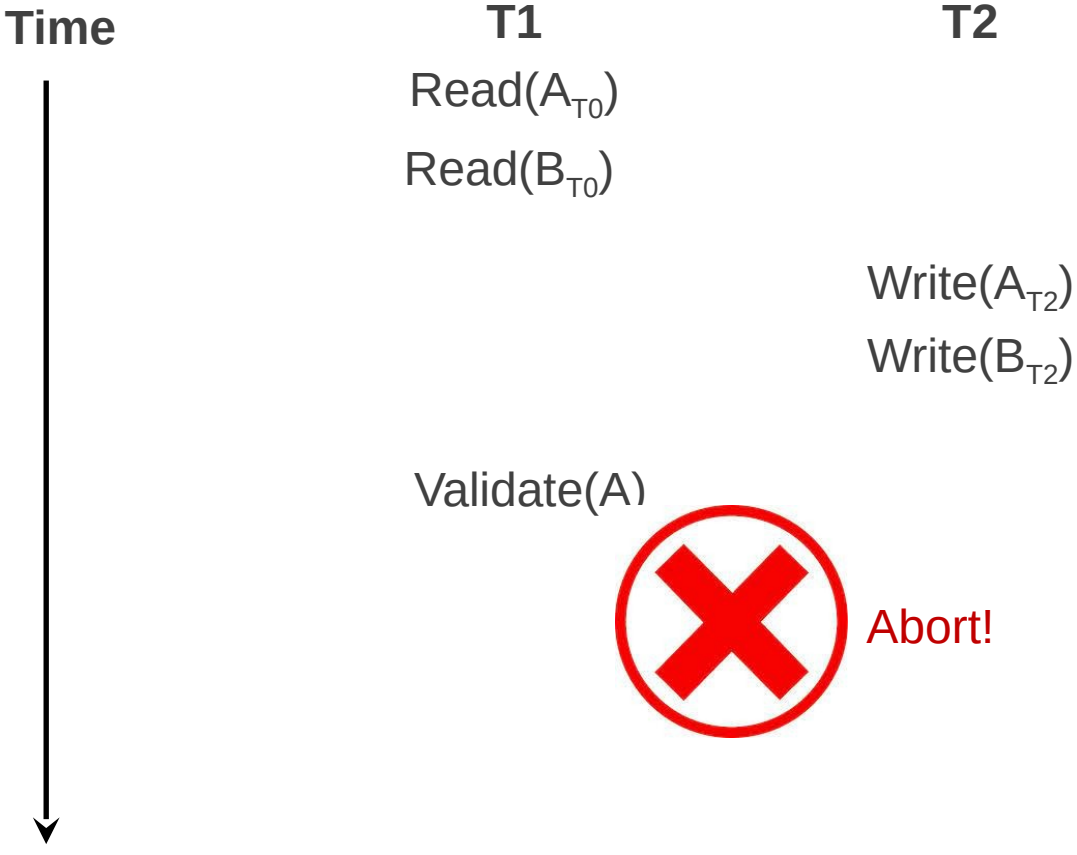


Can we avoid validation for reads?

Abort in OCC

```
T1:
Print(A+B
)
```

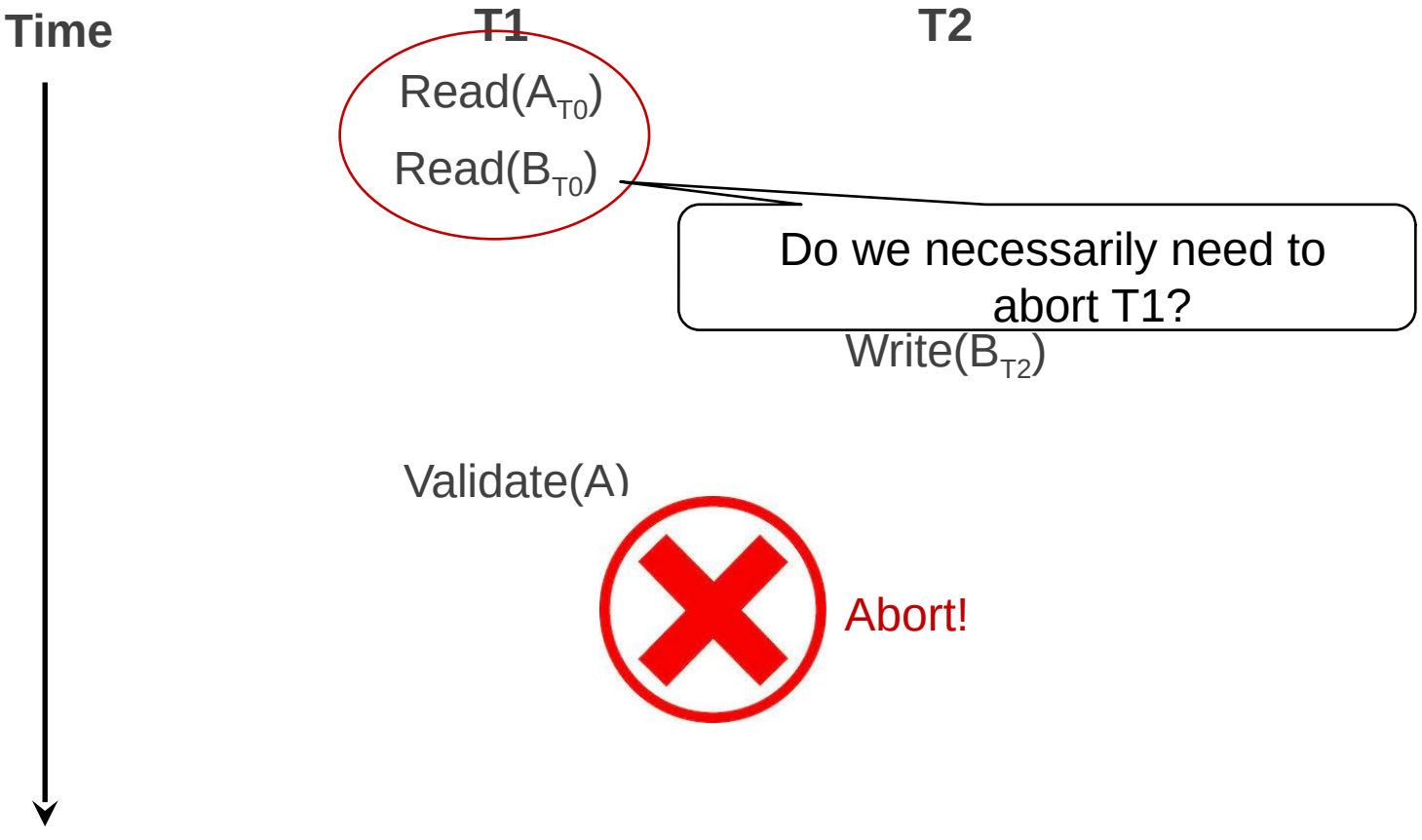
```
T2:
B = 2
A = 3
```



Abort in OCC

```
T1:
Print(A+B
)
```

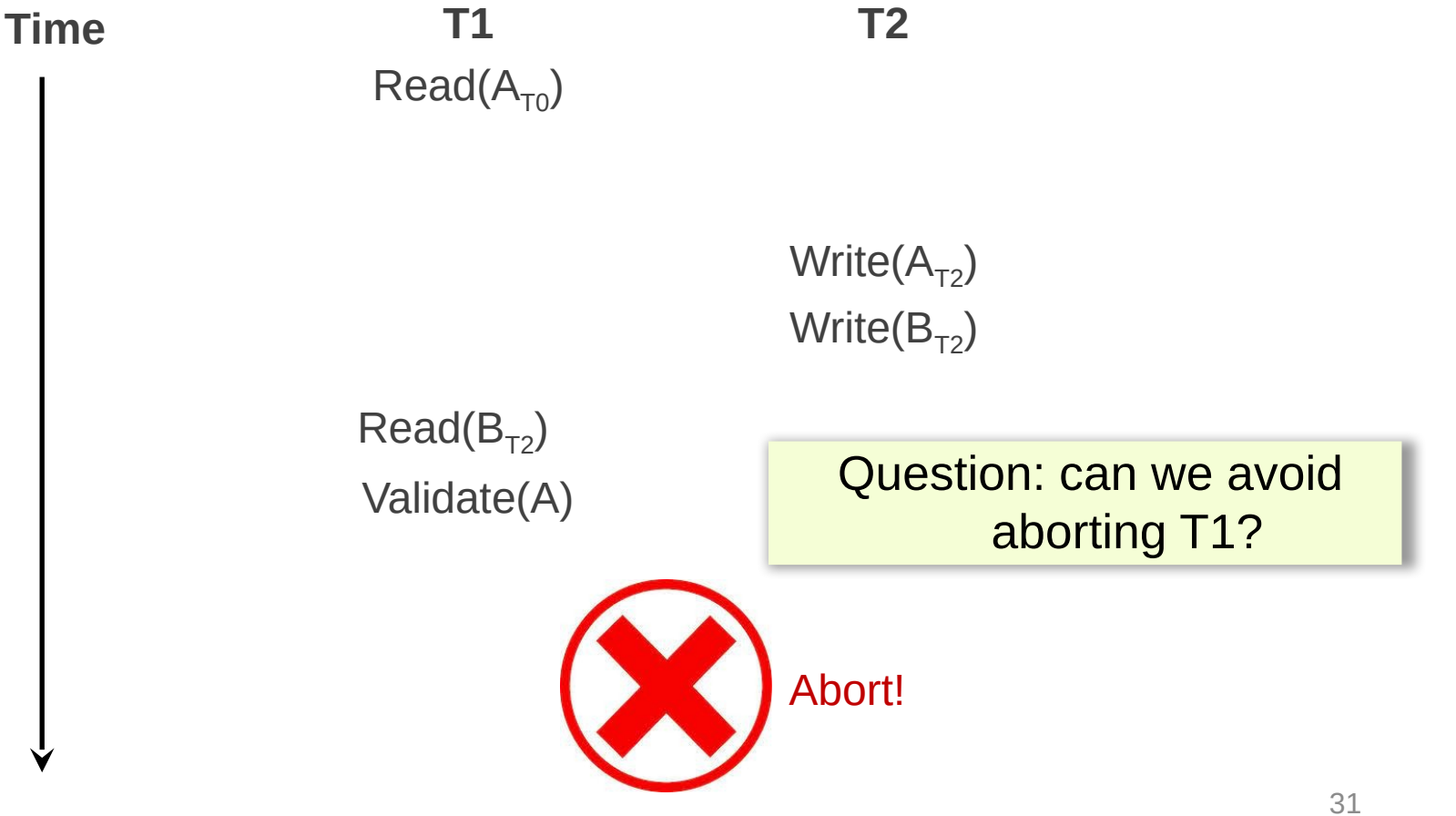
```
T2:
B = 2
A = 3
```



Abort in OCC case (2)

```
T1:
Print(A+B
)
```

```
T2:
B = 2
A = 3
```

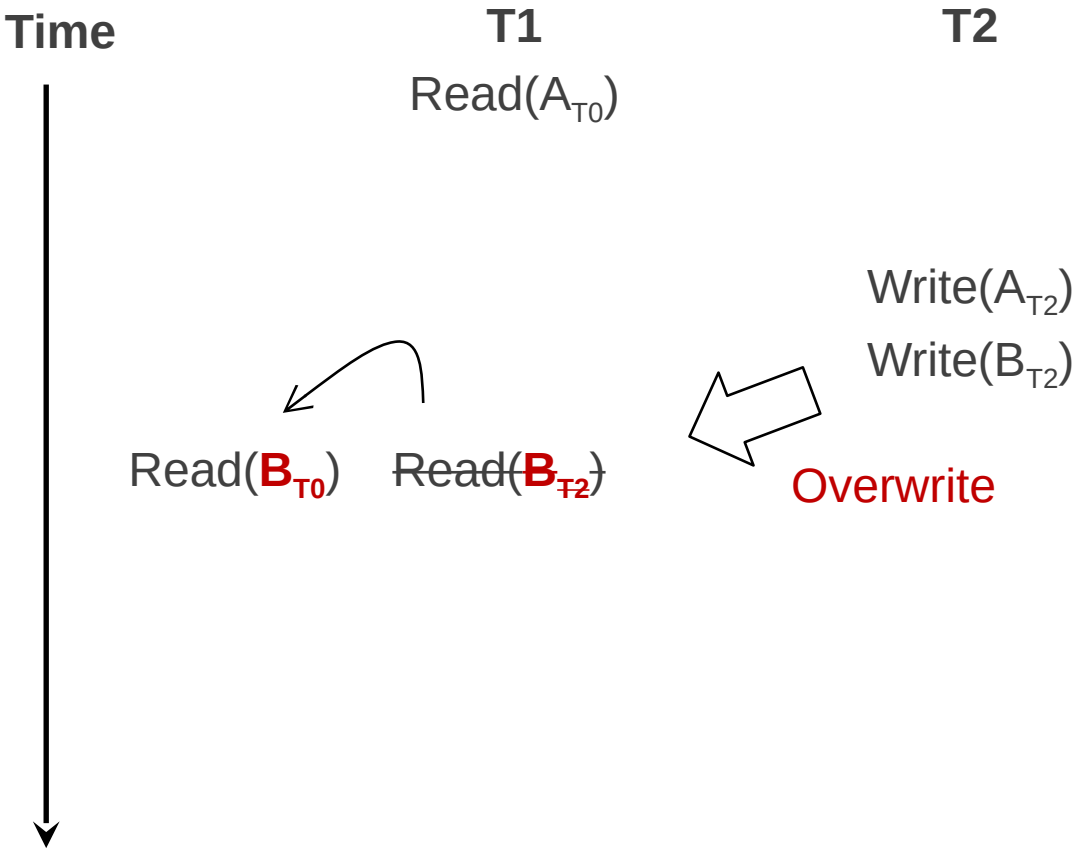


Question: can we avoid aborting T1?

Abort in OCC case (2)

```
T1:
Print(A+B
)
```

```
T2:
B = 2
A = 3
```



Idea: multi-versioning concurrency control

Each data has multiple-versions instead of a single version

- A set of version represents a snapshot of the database
  - E.g., A_{T0} + B_{T0}
- The version ~= the time a TX makes the updates

Data X

```
Struct Data {
 value :  u8[…]
 lock : lock_t
}
```

VersionedData X_0 X_1

```
Struct Data {
 value: List<VersionedData>
 lock : lock_t
}
```

```
Struct VersionedData {
 value: u8[…]
 version: u64
}
```

Idea: multi-versioning concurrency control

Read

- Only read from a consistent snapshot at **a start time**

Write

- Install a new version of the data instead of overwriting the existing one
- Version ~= the **commit time** of the TX

Goal: avoid race conditions on reading a snapshot

Data X

```
Struct Data {
 value :  u8[…]
 lock : lock_t
}
```

VersionedData X_0 X_1

```
Struct Data {
 value: List<VersionedData>
 lock : lock_t
}
```

```
Struct VersionedData {
 value: u8[…]
 version: u64
}
```

Get the start and commit time

Requirement: the counter reflects TX's serial execution order

- E.g., if T1 finishes before T2, it will has a smaller start & commit timestamp

Simplest (& most widely used) solution: global counter

- Using atomic fetch and add (FAA) to get at the TX's begin & commit time
- TX Begin: use FAA to get the start time
- TX Commit: use FAA to get the commit time

We will introduce more advanced timestamps in later lectures

- Not using a global counter is challenging because de-centralized time (e.g., physical time) is unsynchronized

Try #1: Optimize OCC w/ MV (incomplete)

Acquire the start time

Phase 1: Concurrent local processing

- Reads data belongs to the snapshot closest to the start time
- Buffers writes into a write set

Acquire the commit time

Phase 2: Commit the results in critical section

- Commits: installs the write set with the commit time

Compared to the OCC, no validation is need!

Try #1: Optimize OCC w/ MV (incomplete)

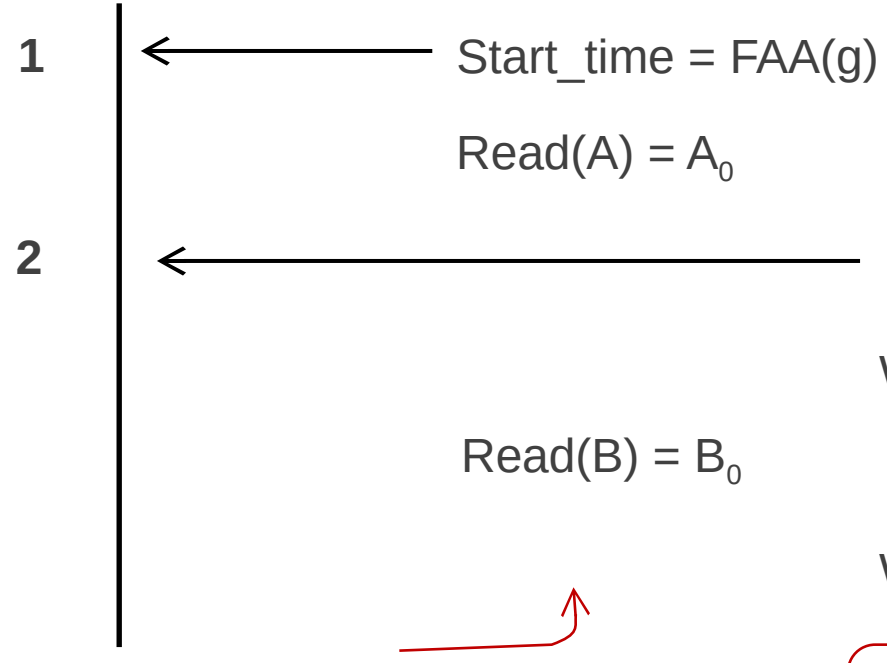
```
Commit(tx):
   for record in tx.write_set:
       lock(record)
   let commit_ts = FAA(global_counter)
   for record in tx.write_set:
       record.insert_new_version(commit_ts, ...)
       unlock(record)


Get(tx, record):


   for version,value in
record.sort_version_in_decreasing():
       if version <= tx.start_time:
          return value
```

Partial snapshot

```
T1:
Print(A+B
)
```
T1

```
T2:
B =
2
A =
3
```
T2

Global counter g (initial 0)



A: A_0
B: B_0

A: A_0
B: **B_2** B_0

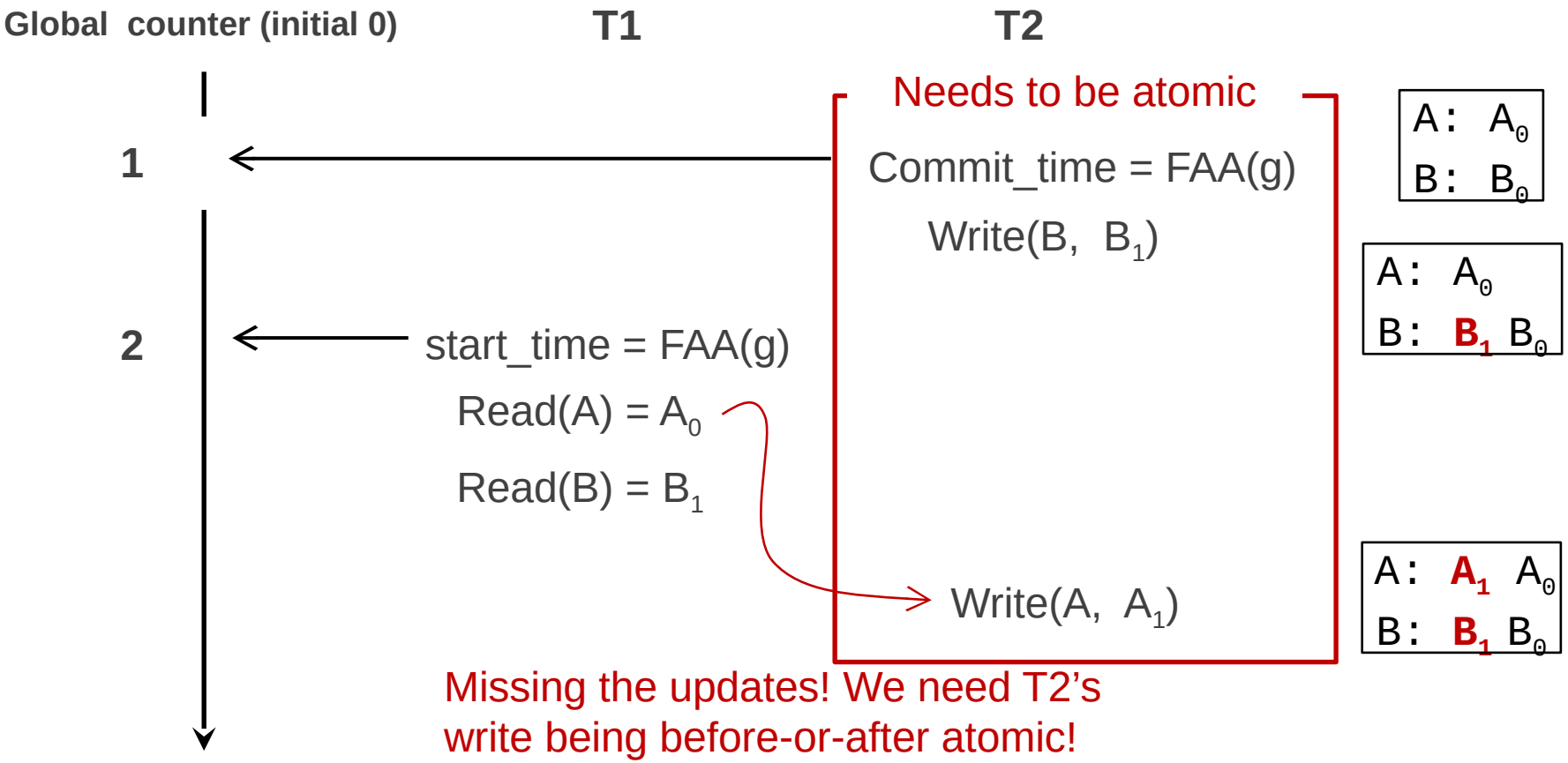
A: **A_2** A_0
B: **B_2** B_0

Problem: partial updated snapshot

Partial snapshot example

```
T1:
Print(A+B
)
```

```
T2:
B = 2
A = 3
```

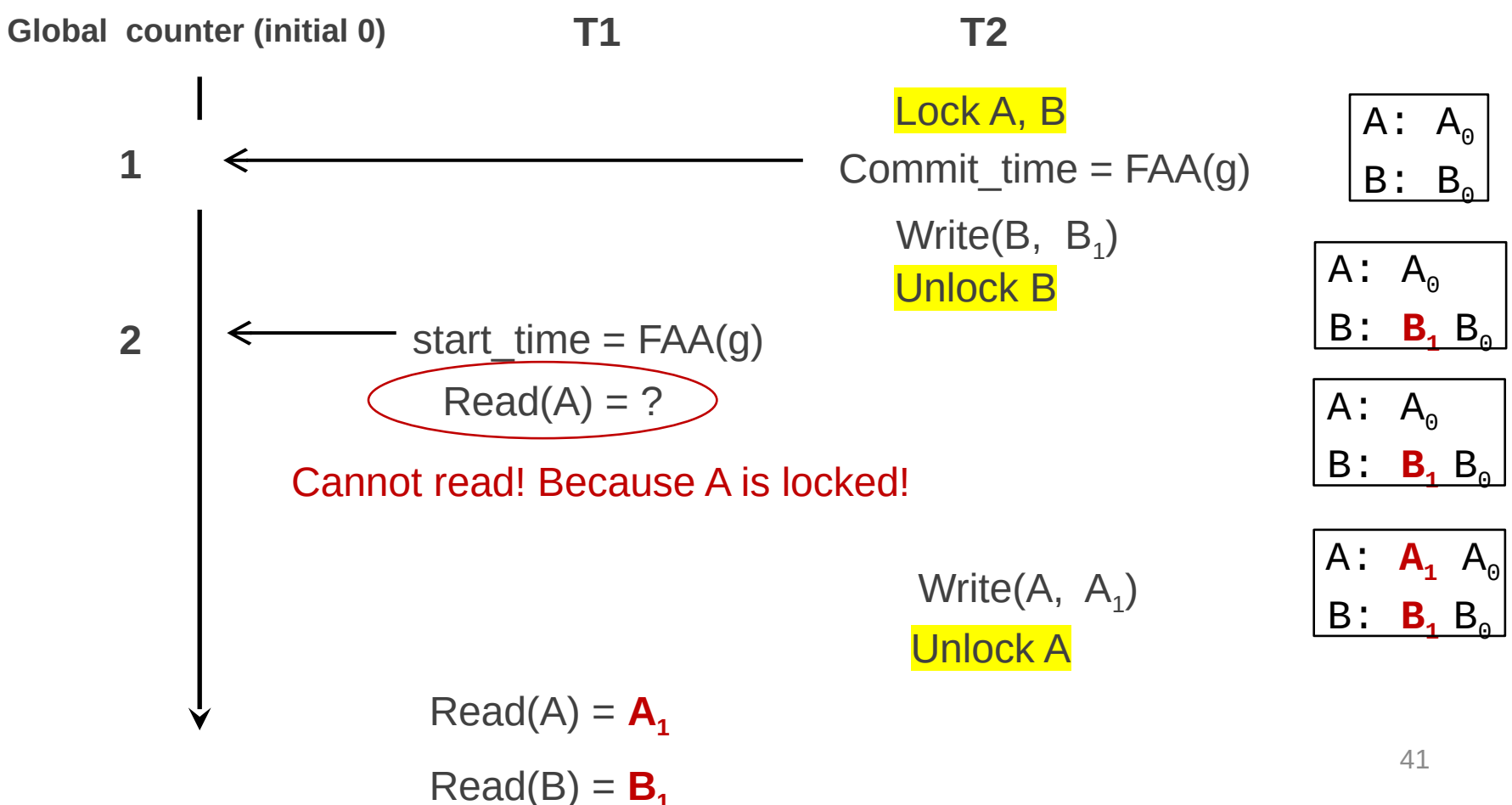


Enforcing the write atomicity of snapshot w/ locking

```
Commit(tx):
   for record in tx.write_set:
       lock(record)
   let commit_ts = FAA(global_counter)
   for record in tx.write_set:
       record.insert_new_version(commit_ts, ...)
       unlock(record)


Get(tx, record):
   while record.is_locked():
         pass
   for version,value in
record.sort_version_in_decreasing():
       if version <= tx.start_time:
          return value
```

Example revisit

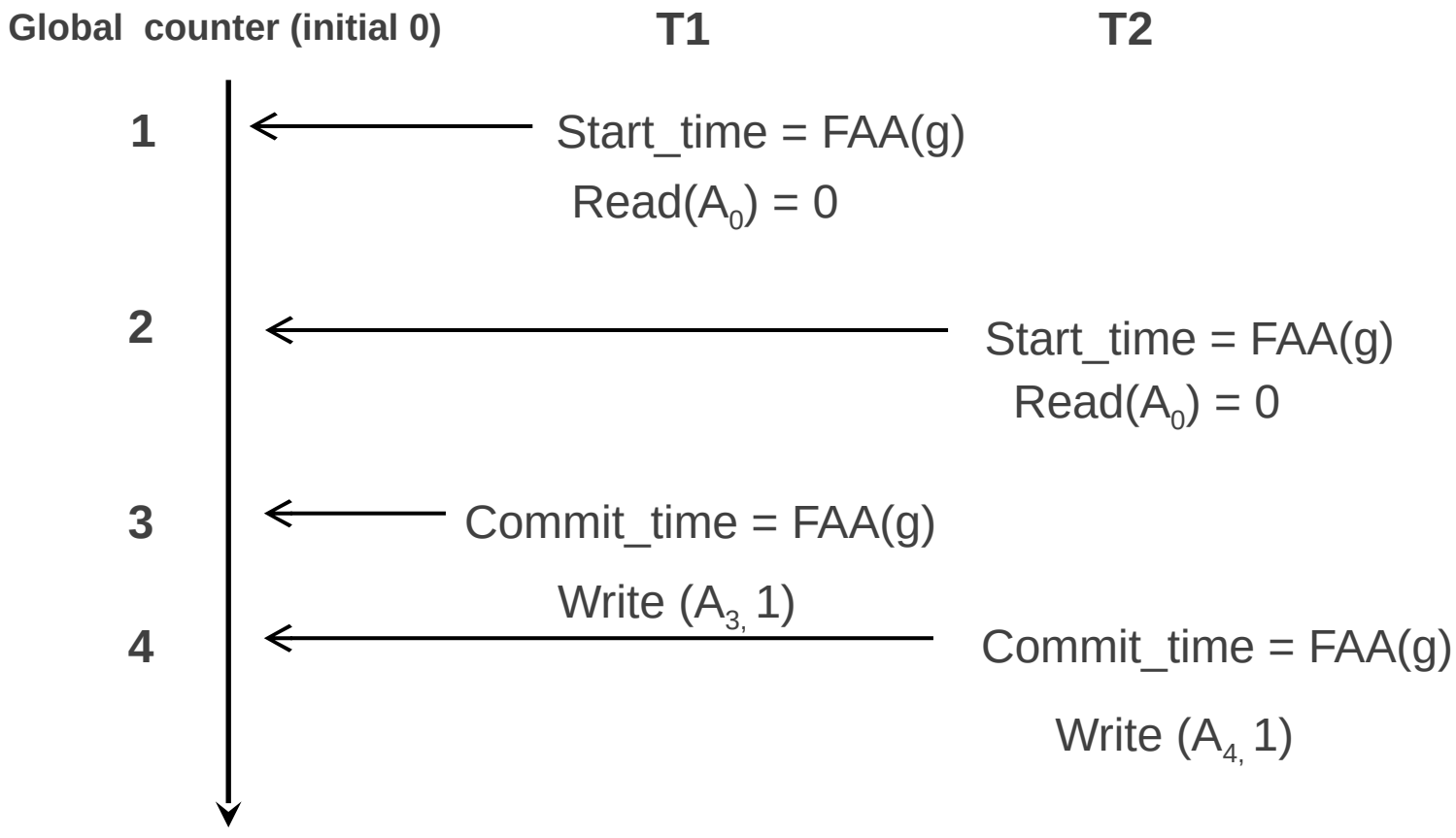
Question: can we reorder get commit time and locking?



What about writes?

```
T1:
A += 1
```

```
T2:
A += 1
```



MVCC ensures no race for reads, but not writes

Race conditions of reads are isolated via snapshots

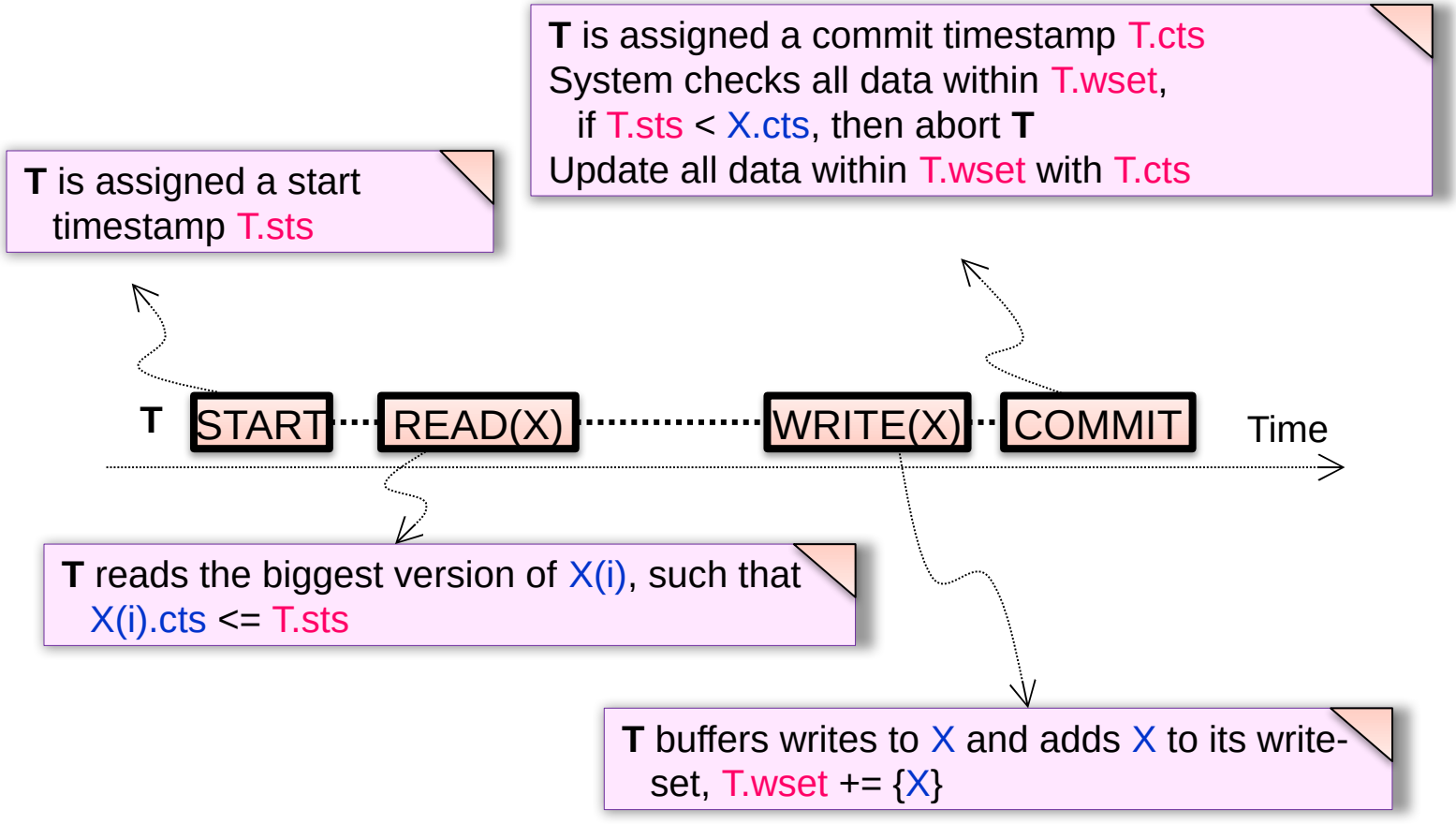
But we still needs to rule out race conditions between reads and writes

- We do so by validating the writes at the commit time

The validation is simple:

- During commit time, check whether another TX has installed a new snapshot after the committing TX's start time

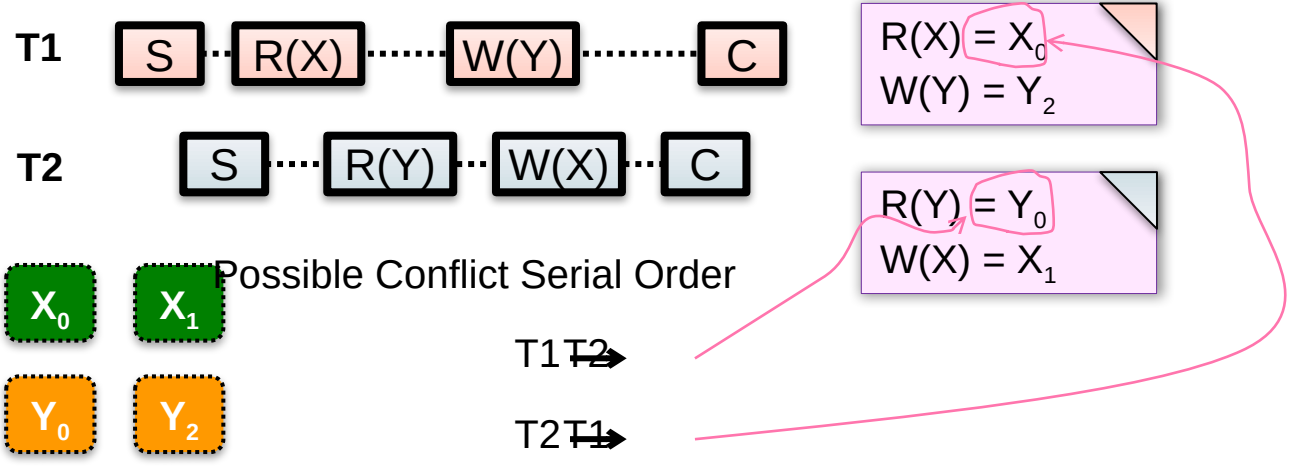
Put it together, MVCC so far



Question: do our current MVCC method guarantee before-or-after?

Write skew anomaly

Our MVCC differs from serializability due to one **anomaly**
Describe the anomaly and also give a concrete application for which the anomaly is undesirable.



Fixing the anomaly

The simplest way is to validate the read-set in read-write TX

- Essentially fallbacks to OCC for read-write TX
- But read-only TX can still enjoy the benefits from MVCC
  - Never aborts & no validations

Usually being ignored in practice (Snapshot isolation)

- The MVCC without the read validation is also called **snapshot isolation (SI)**
- Though the idea of MVCC is first proposed in SI, its usage is not restricted to it, e.g., we can have MV-2PL and MV-OCC; & we will see it later

Multi-site transaction &
Multi-site atomicity

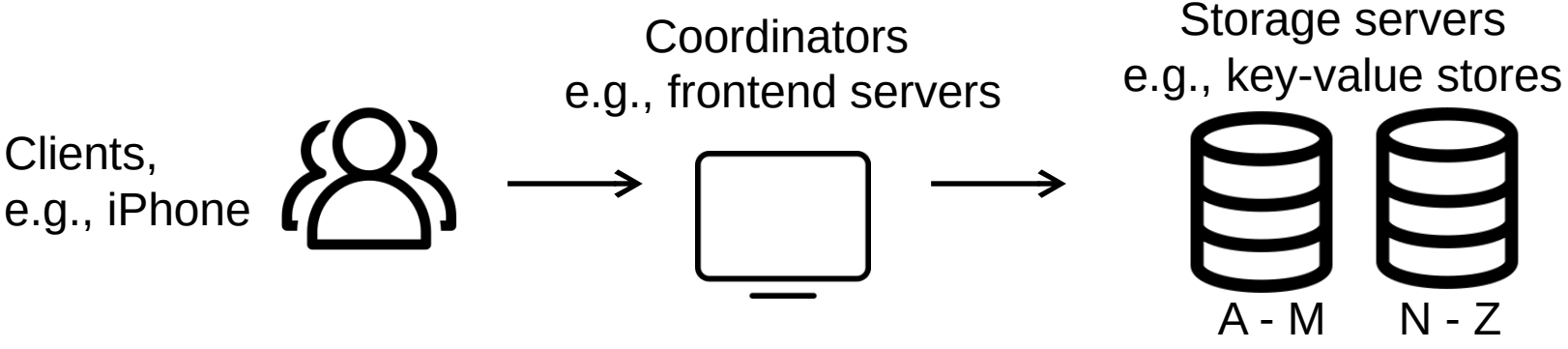
Multi-site transaction: what if the data is distributed?

The data accessed by TXs are stored on multiple machines

- i.e., a single site cannot store all the bank accounts

The setup

- Client + coordinator + two servers
- One server handles bank accounts A-M
- The other server handles bank accounts N-Z
- Coordinator and servers all have logs to ensure single transaction atomicity

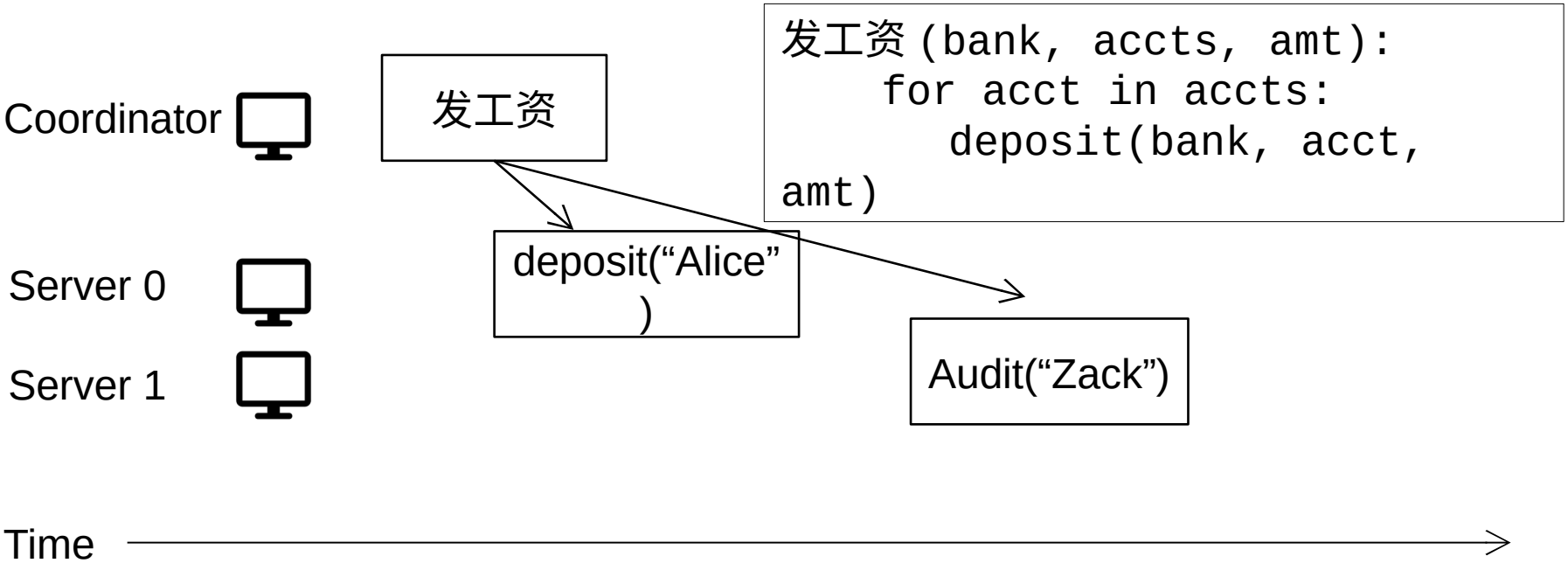


Multi-site transaction

```
Deposit(bank, a, amt):
  bank[a] += amt
```

e.g., coordinator sends multiple deposit to different servers

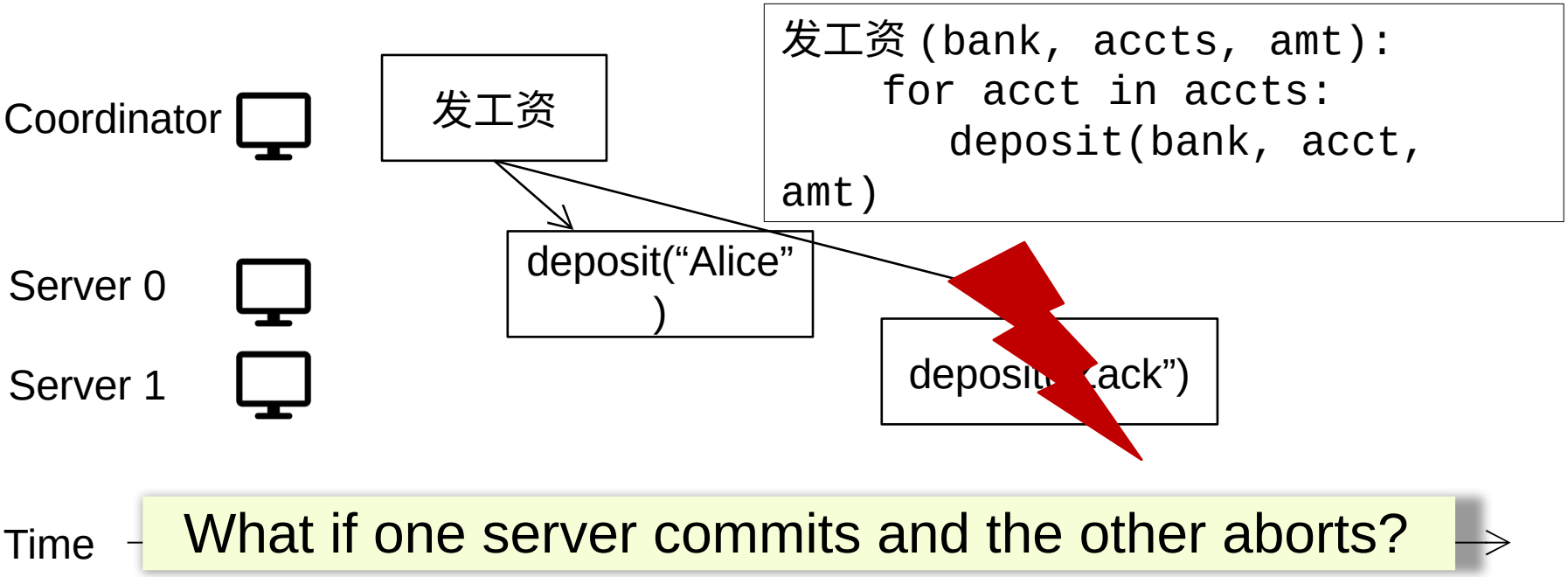
- They use RPCs to send requests to the server to execute transaction



Multi-site transaction

Coordinator sends multiple deposit to different servers

- They use RPCs to send requests to the server to execute transaction



Goal: all sites either all commits or all aborts

Two-phase Commit: a way to ensure multi-site atomicity

High-layer TX

- The high-level view of the TX

Low-layer TX

- Specific reads and writes that executed on a single machine

Higher-layer transaction coordinates the execution of lower-layer TXs

- All low-layer TX either all commits or all aborts

```
发工资(bank, accts, amt):
    tx.high_begin()
    for acct in accts:
       deposit(bank, acct,
amt)
    tx.high_com
```

High-layer TX

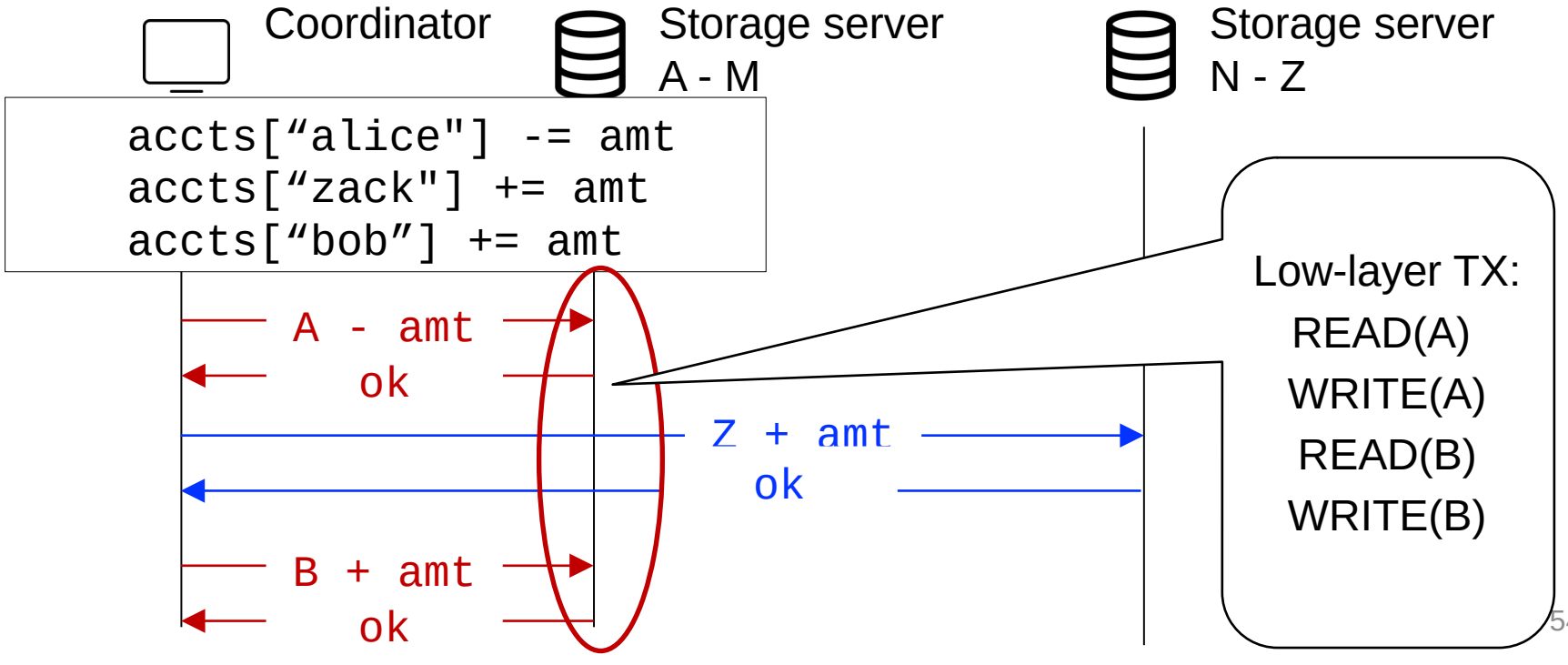
```
Deposit(bank, a, amt):
    tx.low_begin()
    bank[a] += amt
    tx.low_commit()
```

Low-layer TX

We also aggregate scattered accesses as low-layer TX

The coordinator can send scattered reads/writes to a site

- The reads and writes on that site also form a low-layer TX



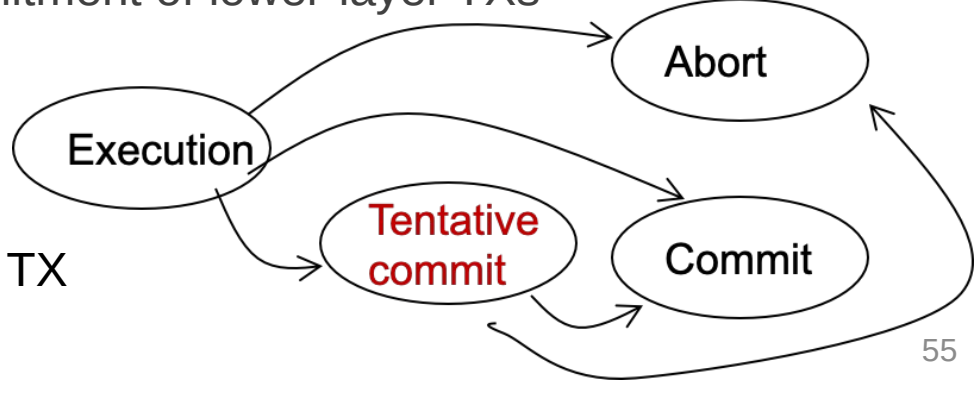
Two-phase Commit: a way to ensure multi-site atomicity

Phase-1: preparation / voting

- Delay the commitment of low-layer TXs
- Lower-layer transactions either abort or *tentatively* committed
- Higher-layer transaction evaluate lower situation

Phase-2: commitment

- The high-layer decides whether low-layer TXs will commit or abort
- It will also coordinate the commitment of lower-layer TXs



State transitions of a TX

Two-phase Commit: a way to ensure multi-site atomicity

High-layer TX

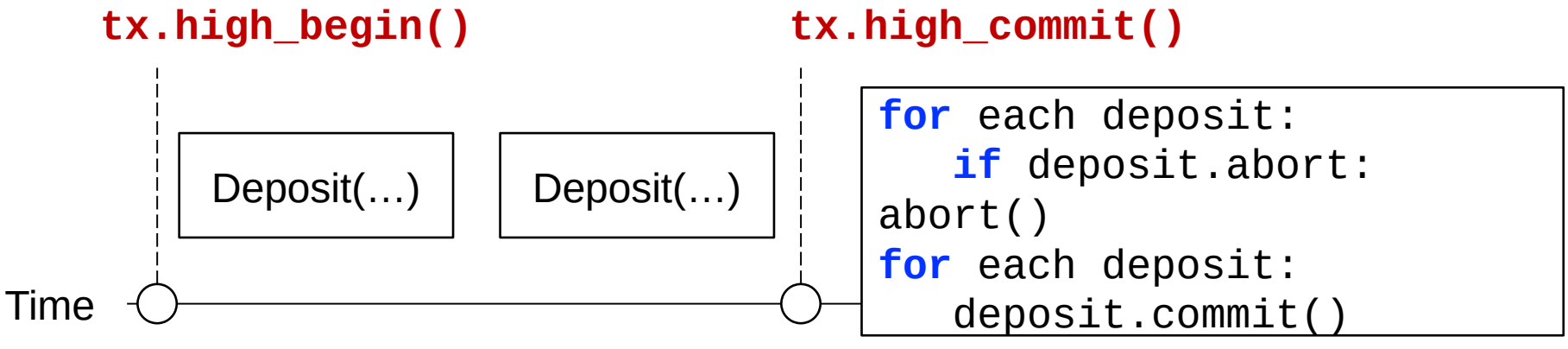
```
发工资(bank, accts, amt):
    tx.high_begin()
    for acct in accts:
        deposit(bank, acct, amt)
    tx.high_commit()
```

High_begin

- Mark itself as a high-level transaction

High_commit

- Send prepare messages to the low-level transactions to check whether it can commit



We need extension to the low-layer TX's lo

Low-layer TX

Recall: the WAL logging in lecture 10

- At commit point, append a commit record to the log

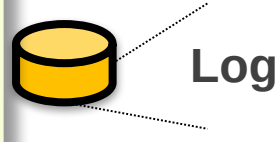
Question

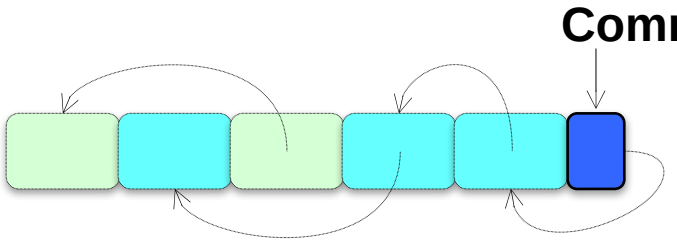
- Can we directly append the commit record to the lower-level transaction log?

```
Deposit(bank, a, amt):
    tx.begin()
    bank[a] += amt
    tx.commit()
```

```
...
log.append("TX {id} commit").sync()
...
```

No! The high-level transaction can abort





Logging rule of WAL under 2PC

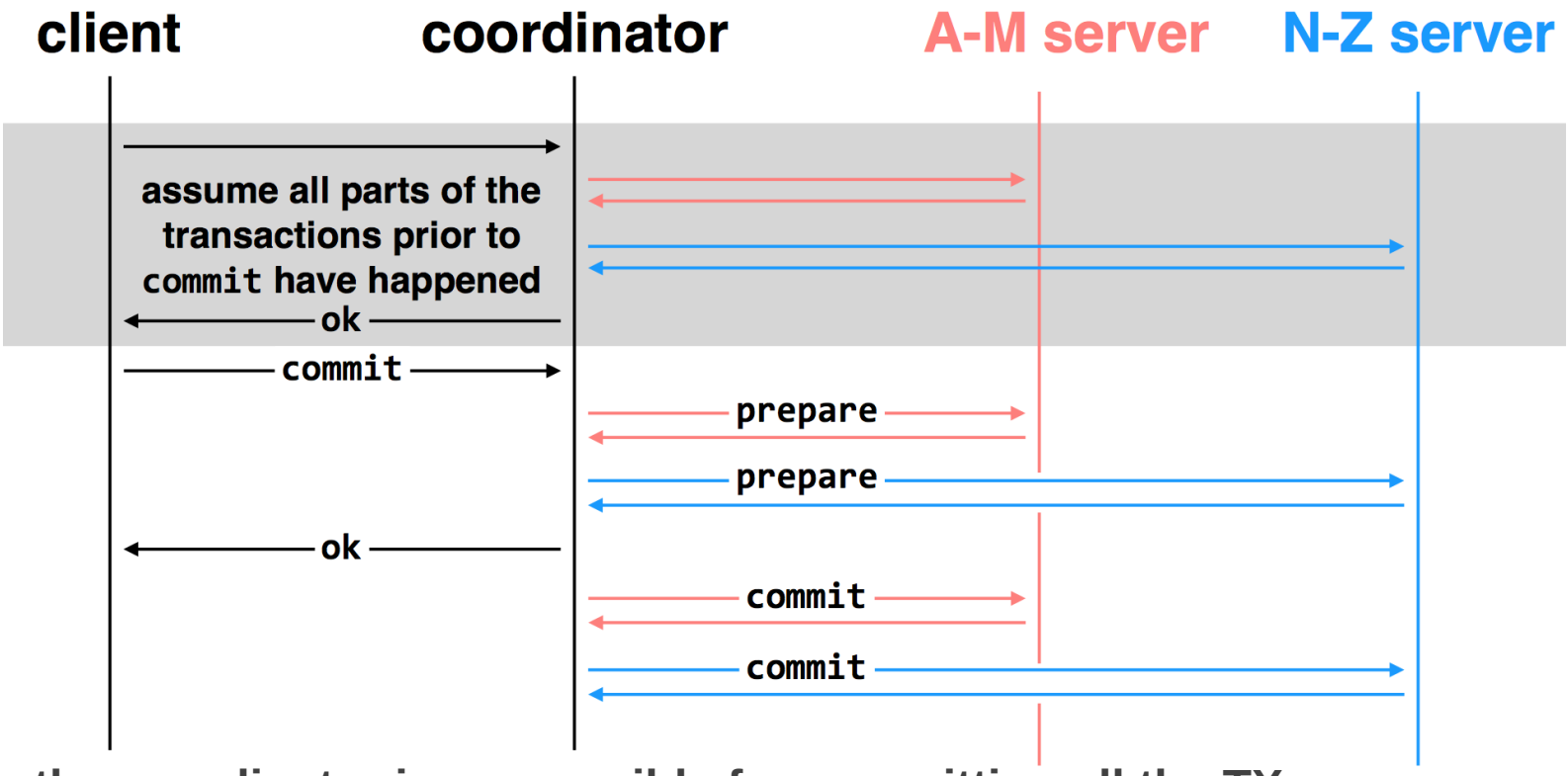
Low-layer transaction

- REDO-UNDO log entries: like normal
- Commit log entry -> Tentative commit log entry **(PREPARED)**
  - Contains a reference to the high-layer TX
  - In case of failure: ask the high-layer TX's coordinator to see if I can commit

High-layer transaction （Responsible for commit of low-layer TXs)

- Log the prepare log as a commitment of a high-layer TX

Multi-site transactions under two-phase commit



Idea: the coordinator is responsible for committing all the TXs

How? By sending RPCs or Messages to all the other servers

Challenge: unreliable communications, coordinator & worker

Multiple-site Atomicity

Principles:

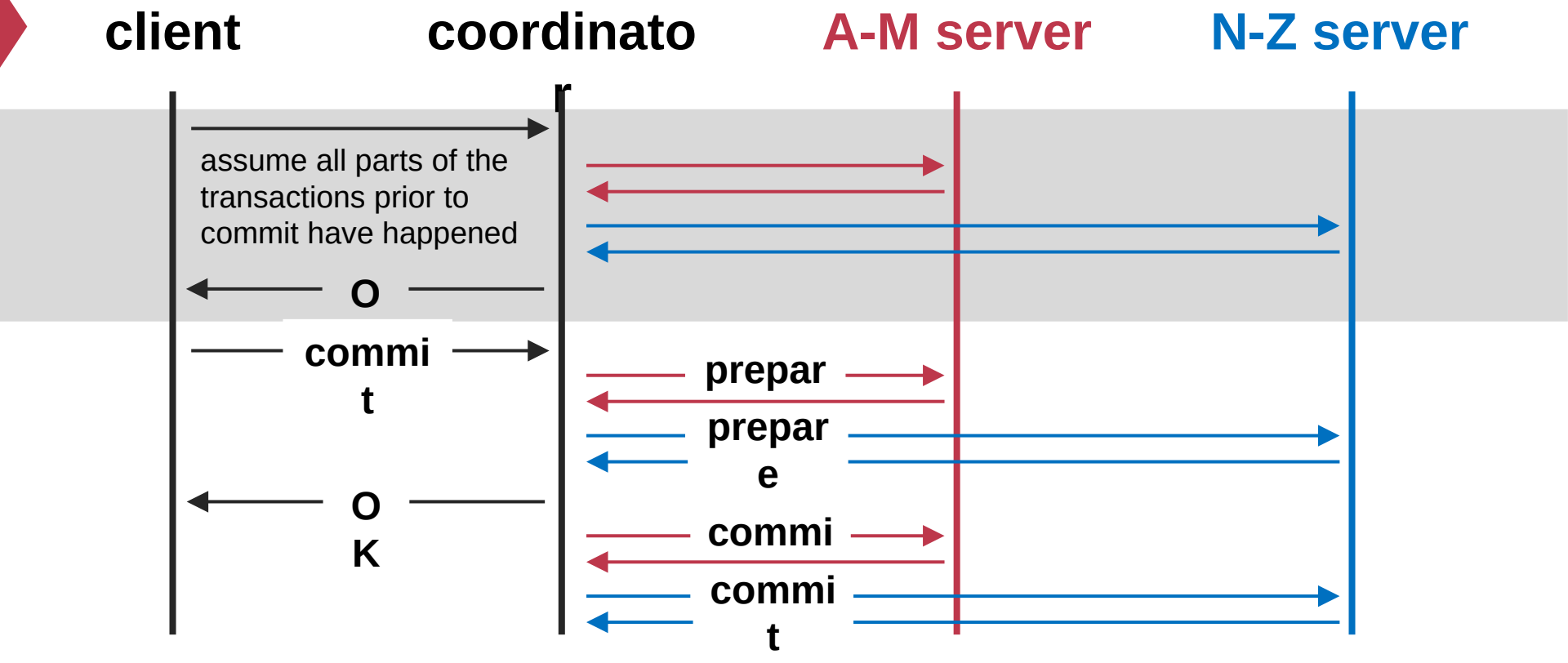
- Following the coordinator's decision
- Log sufficient state to tolerate failures (e.g., the coordinator's decision)

Coordinator (do the decision & maintain the state)

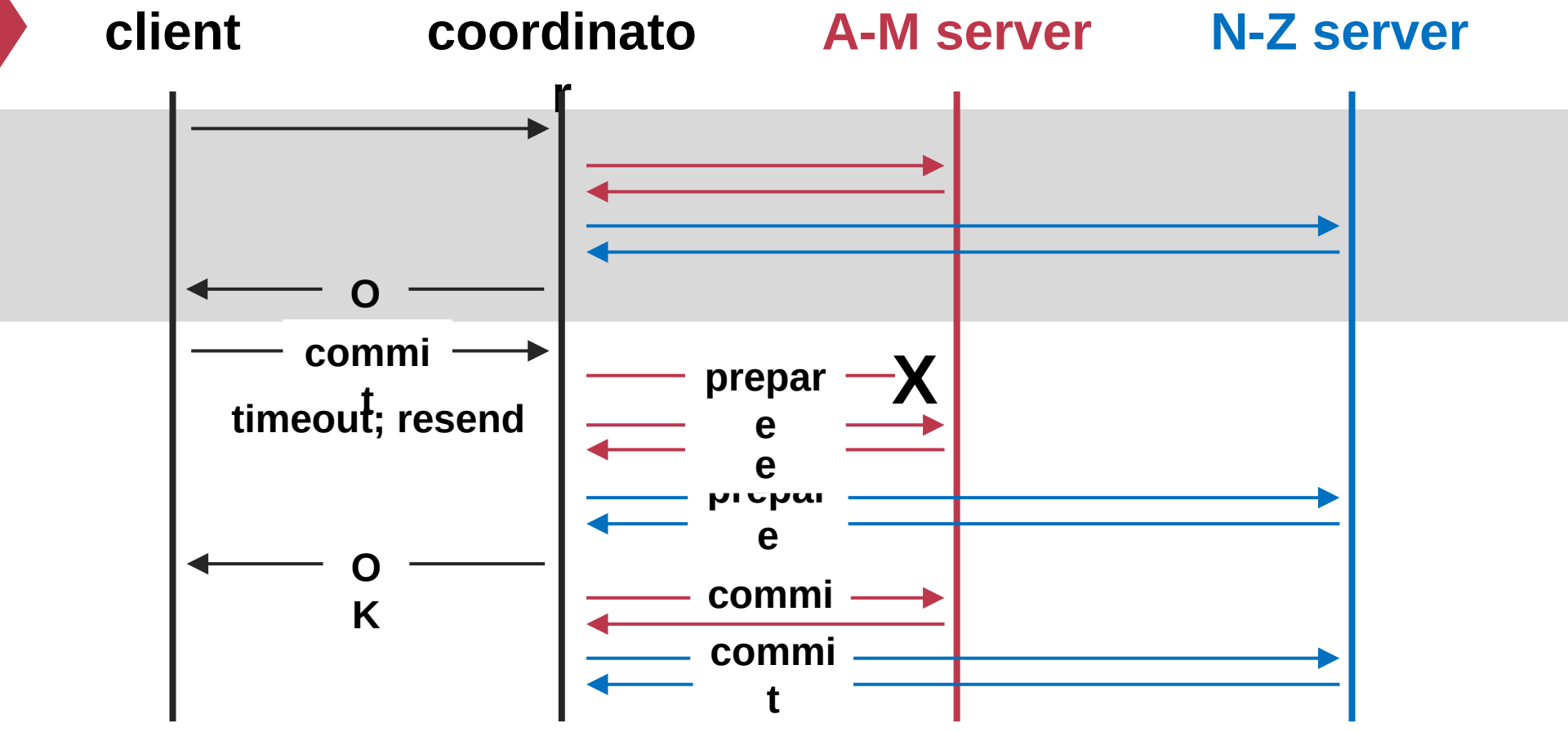
- Collect some **ABORT** or nothing: **ABORT** or retry
- Collect all **COMMIT**: then **COMMIT**

Worker passively react to the coordinator's actions

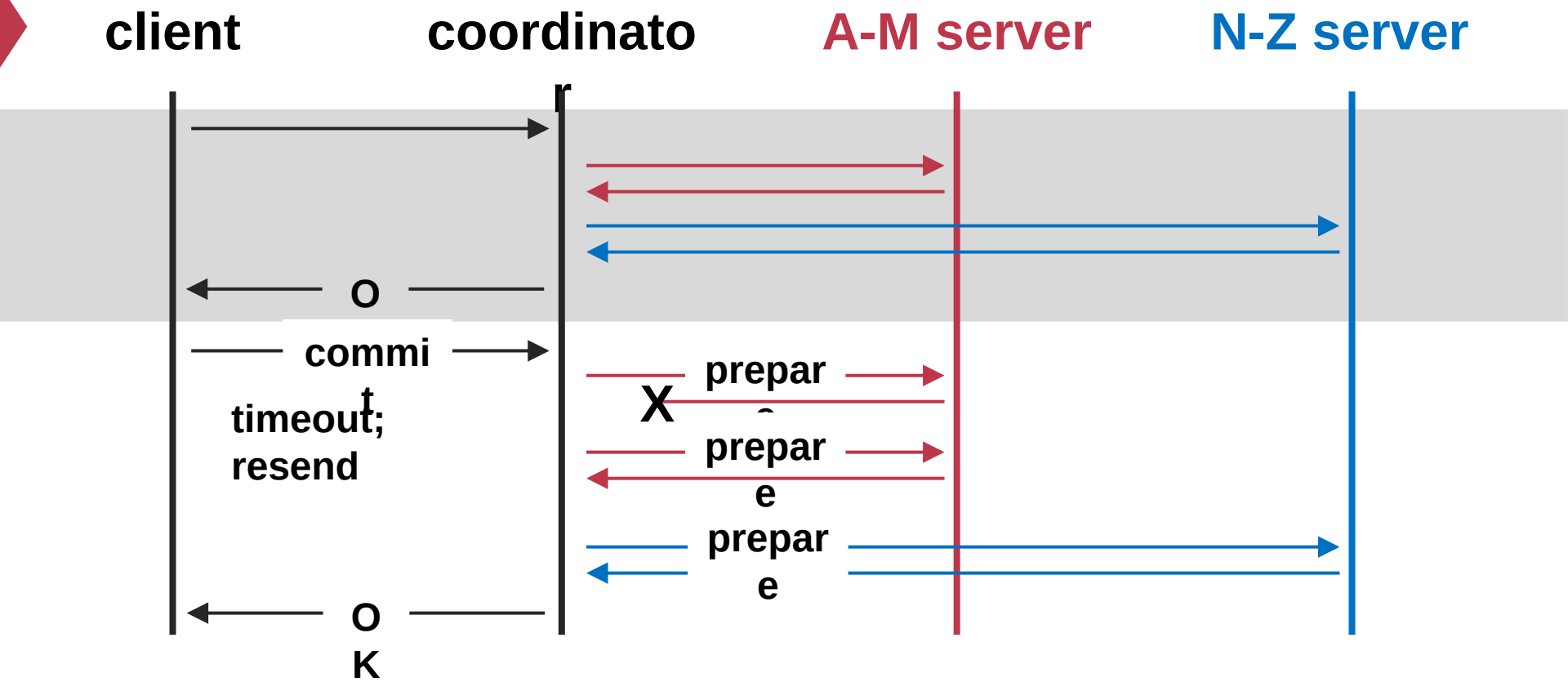
- If no message is sent from the coordinator, just wait
- When receive **COMMIT**: then **COMMIT**



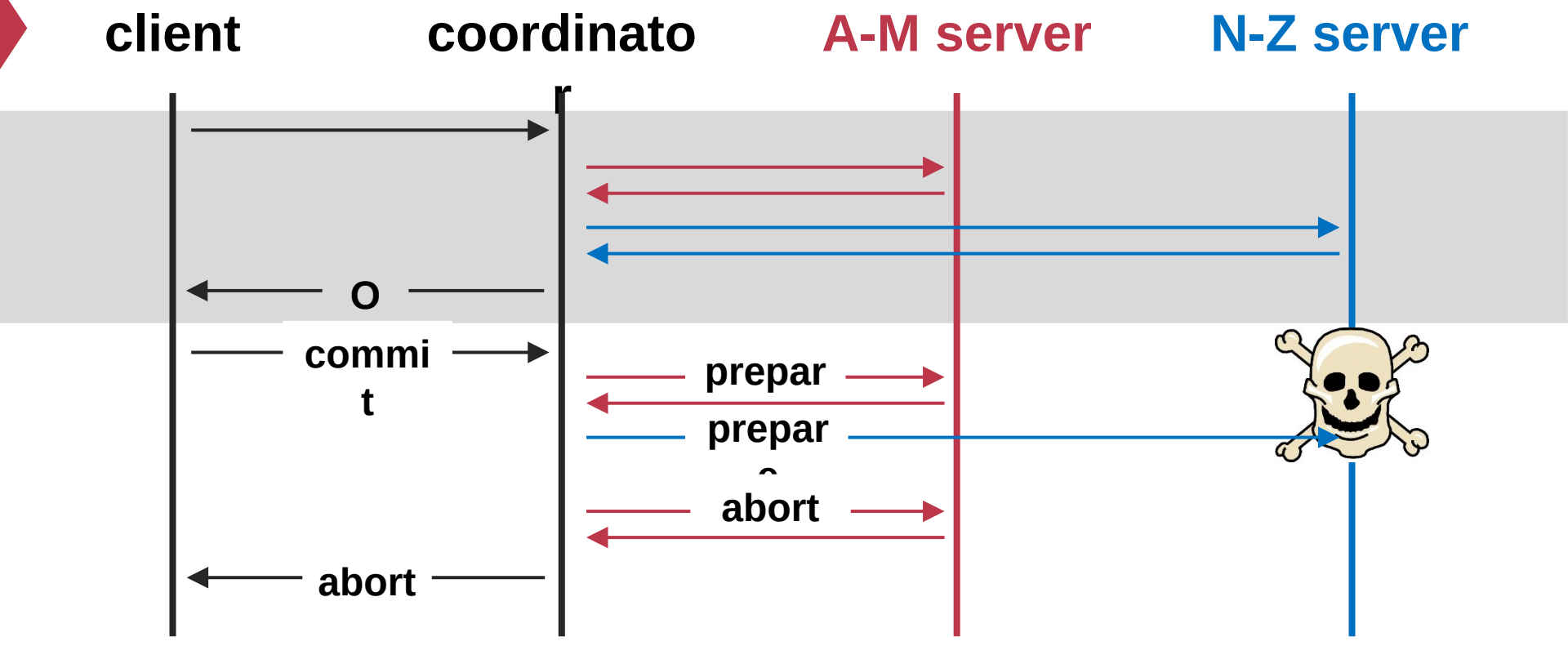
two-phase commit: nodes agree that they are ready to commit before committing



failure: lost prepare

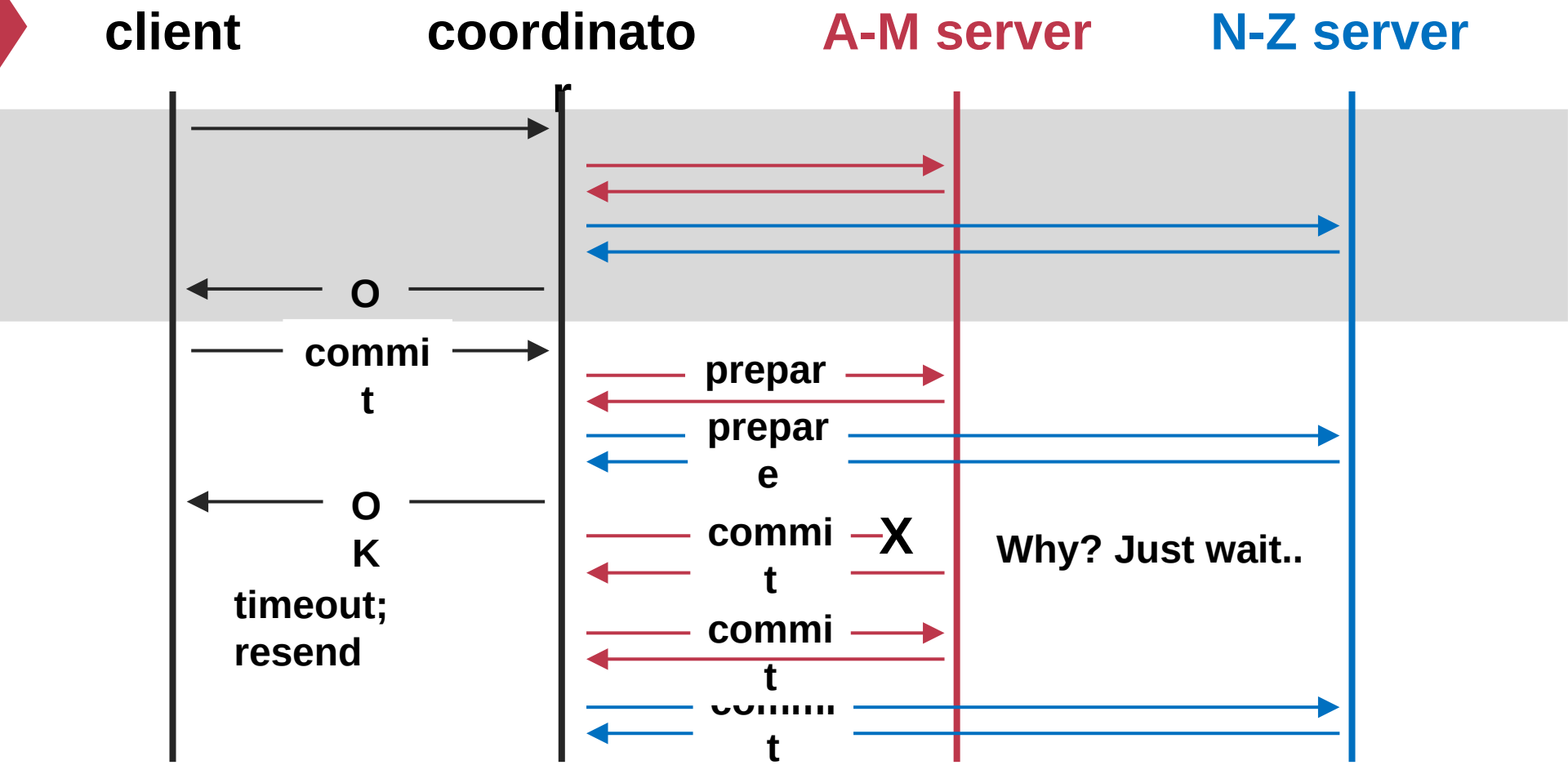


failure: lost **ACK** for **prepare**

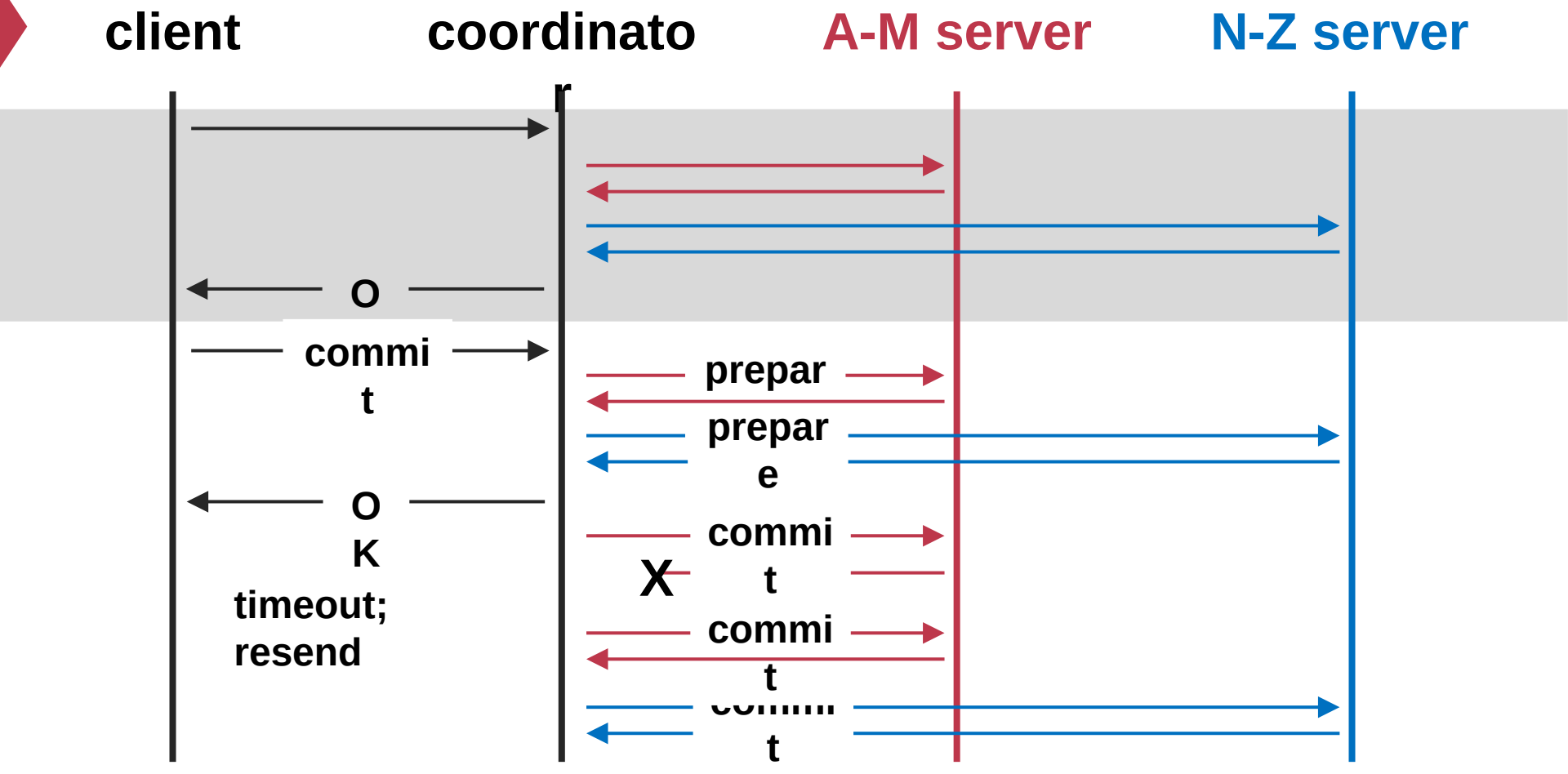


failure: **worker failure during prepare**

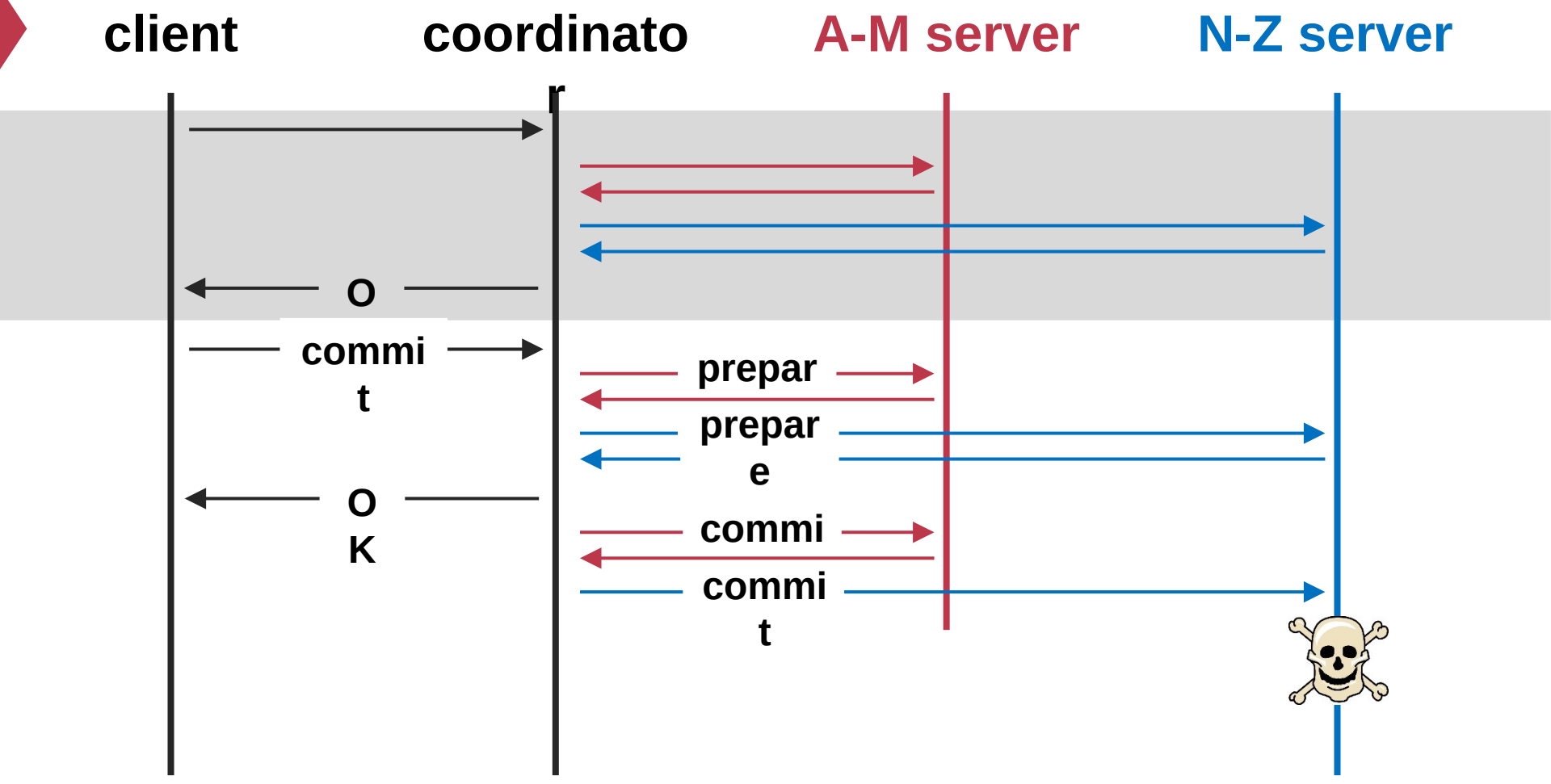
coordinator can safely abort transaction, will send explicit abort messages to live workers



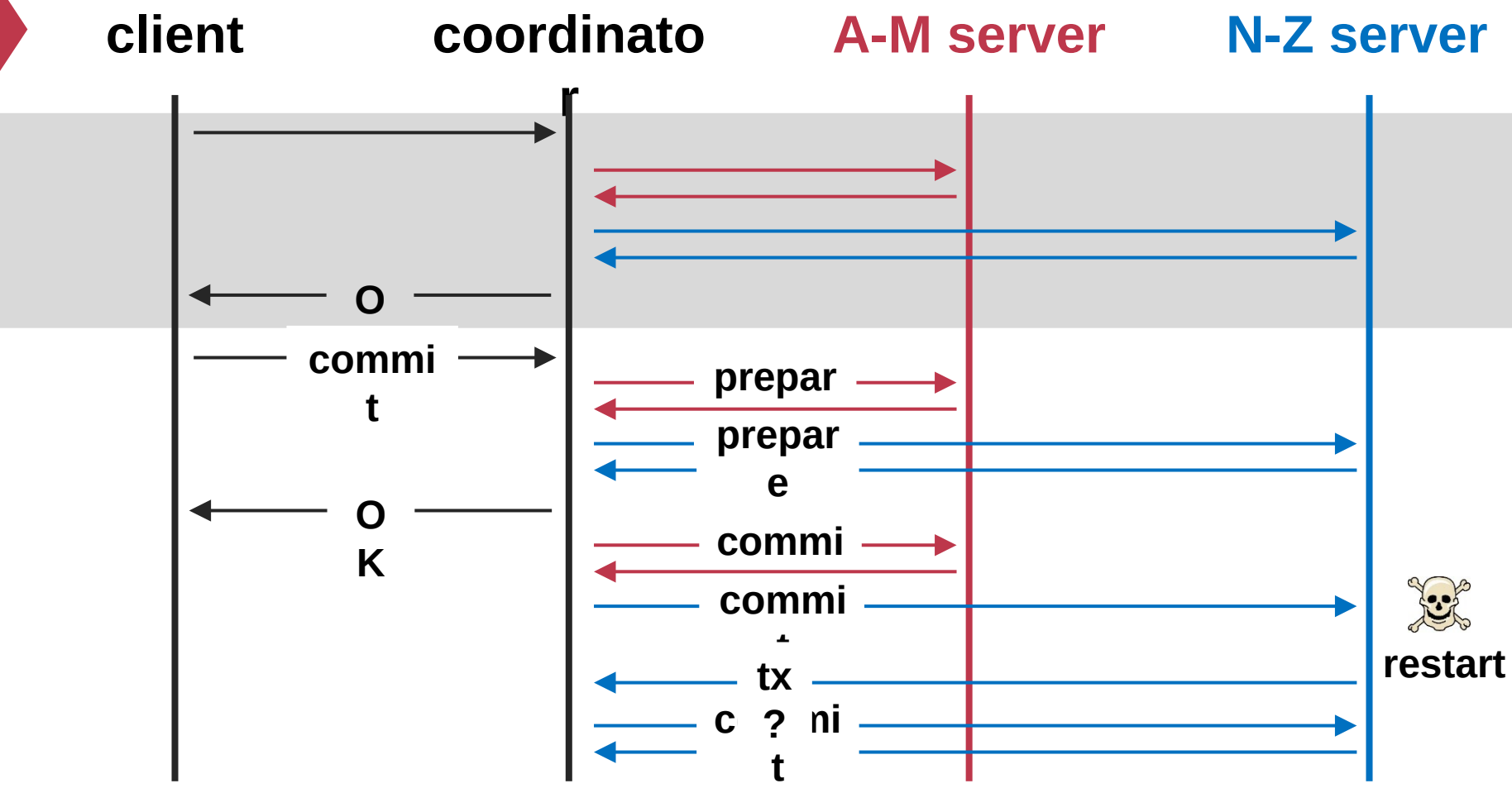
failure: lost commit message



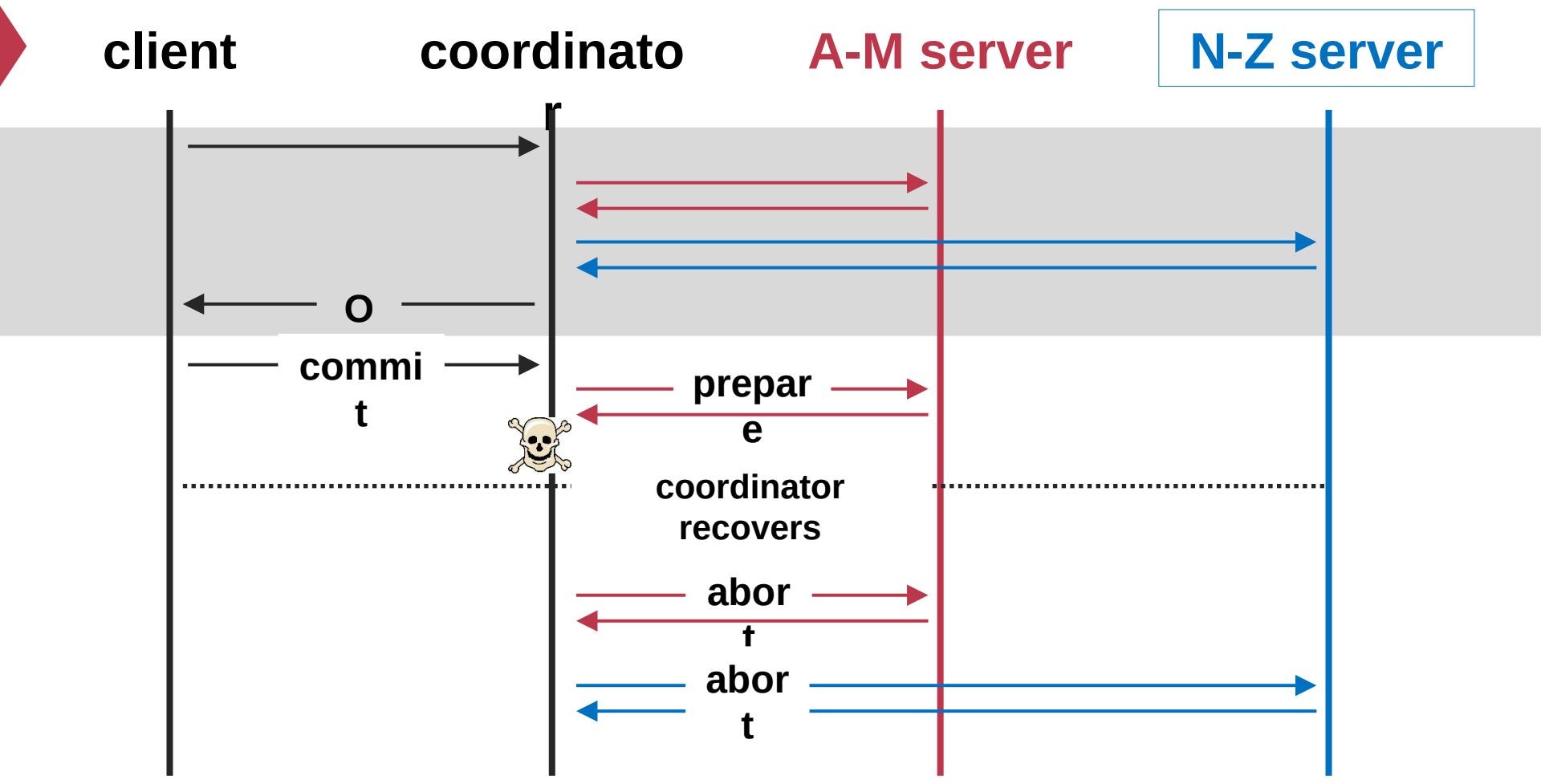
failure: lost ACK of commit message



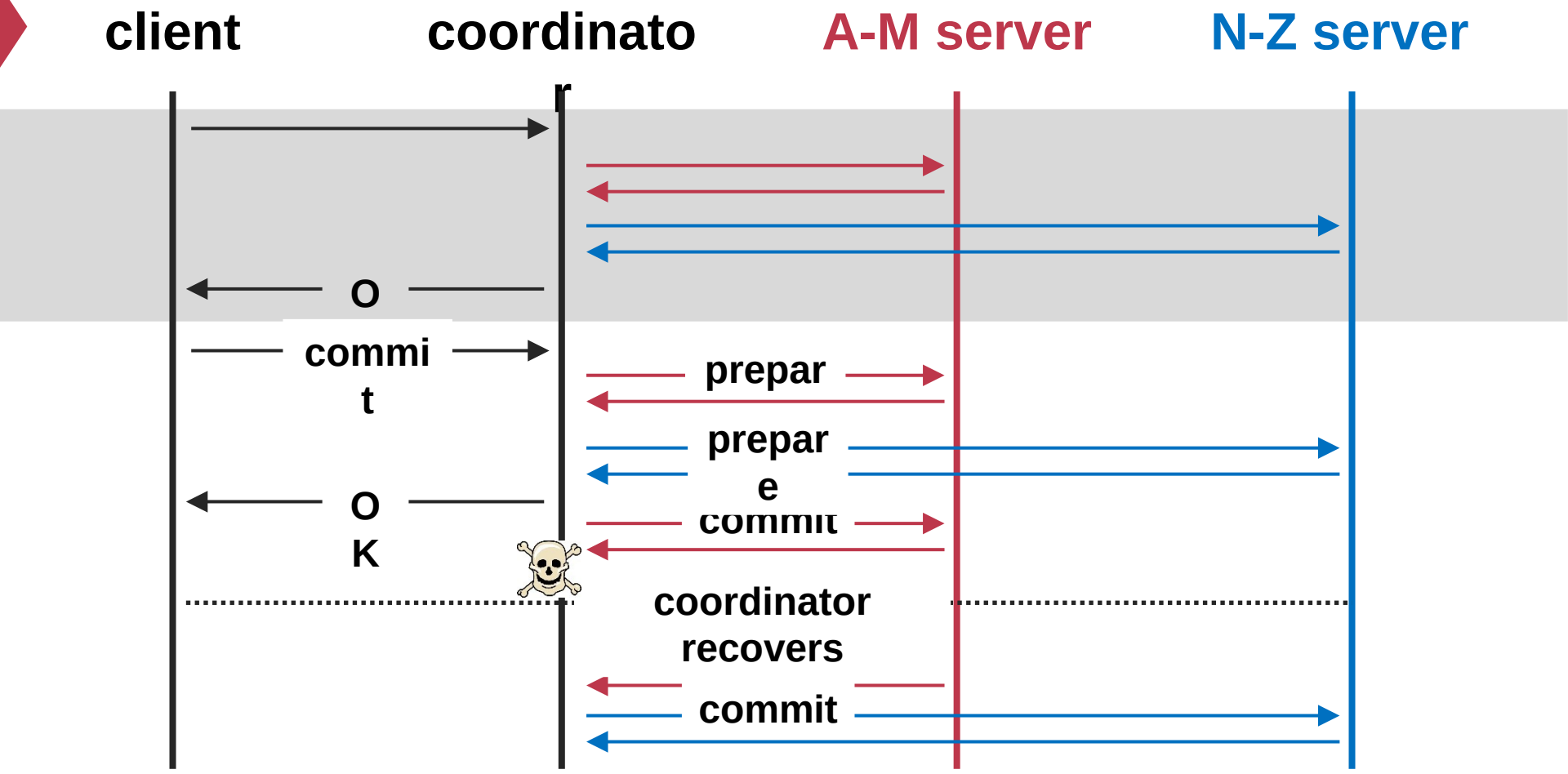
failure: worker failure during commit



failure: worker failure during commit



failure: coordinator failure during prepare



failure: coordinator failure during commit

Must log the decision before sending the commit messages

What about 2PL or OCC in 2PC?

Nearly identical

- 2PL: each low-layer TX cannot release its lock until the high-layer TX decides to commit
- OCC: the validation & commit phases are done by the coordinator

Summary of 2-phase Commit

Two-phase commit allows us to achieve **multi-site atomicity**: transaction remains atomic even when they require communication with multiple machines

In two-phase commit, failures prior to the commit point can be aborted. If workers (or the coordinator) fail after the commit point, **they recover into the PREPARED state**, and complete the transaction

Remaining challenge: availability under coordinator failures

- Follow the coordinator's decision simplifies achieving multi-site atomicity, but what if the coordinator crashes for a long time?
- We will see how to make the coordinator available in the next lecture