DISTRIBUTED TRANSACTIONS VIA TOTALLY-ORDERED MULTICAST AND TWO-PHASE COMMIT

Module 4
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ATTRIBUTION

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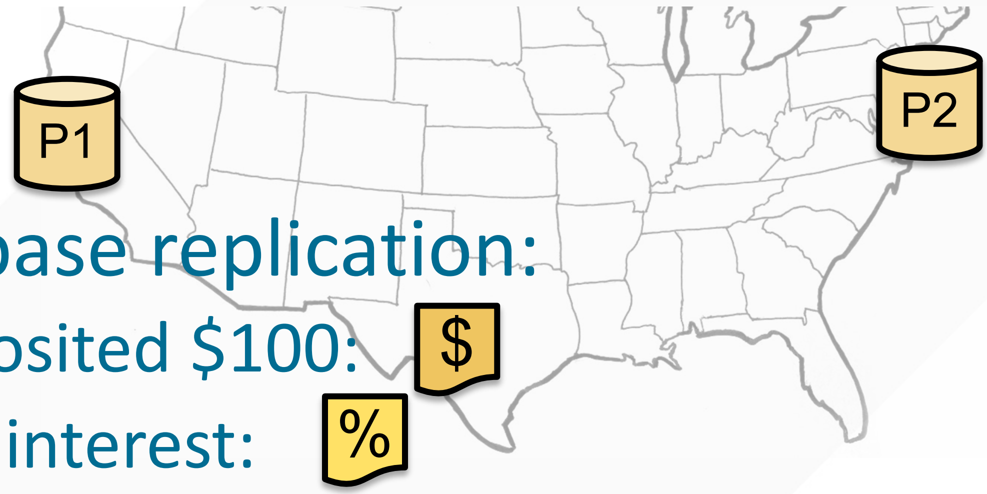
MAKING CONCURRENT UPDATES CONSISTENT



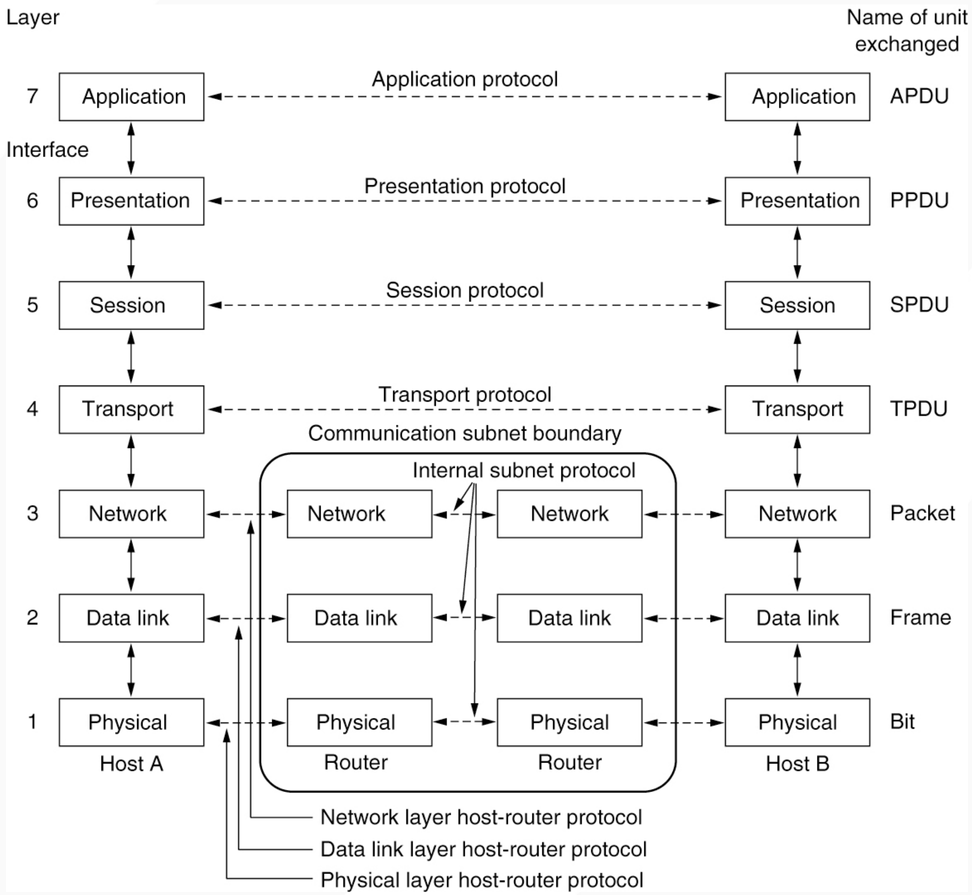
- Recall multi-site database replication:
  - San Francisco (**P1**) deposited $100:
  - New York (**P2**) paid 1% interest:

We reached an inconsistent state due to the "best effort" IP packet delivery model

Could we make a stronger packet delivery model based on the Lamport Clock total order to ensure multicast packets arrive in a consisten order?

DISTRIBUTED TRANSACTIONS AT THE TRANSPORT LAYER

Totally-ordered multicast

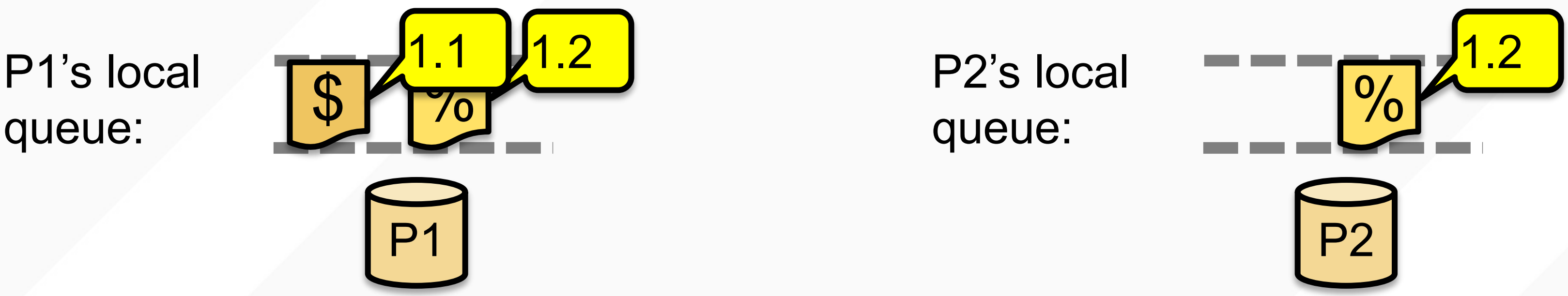


- N processes
- Packet p sent by process Pi arrives to every other process
- Every process receives packets {p0, p1, p2, …} in a consistent total order
  - Though not necessarily at the same physical times

TOTALLY-ORDERED MULTICAST

- Client sends update to **one replica** → **Lamport timestamp C(*x*)**

- **Key idea:** Place events into a **local queue**
  - **Sorted** by increasing C(x)



Goal: All sites apply the updates in (the same) Lamport clock order

TOTALLY-ORDERED MULTICAST

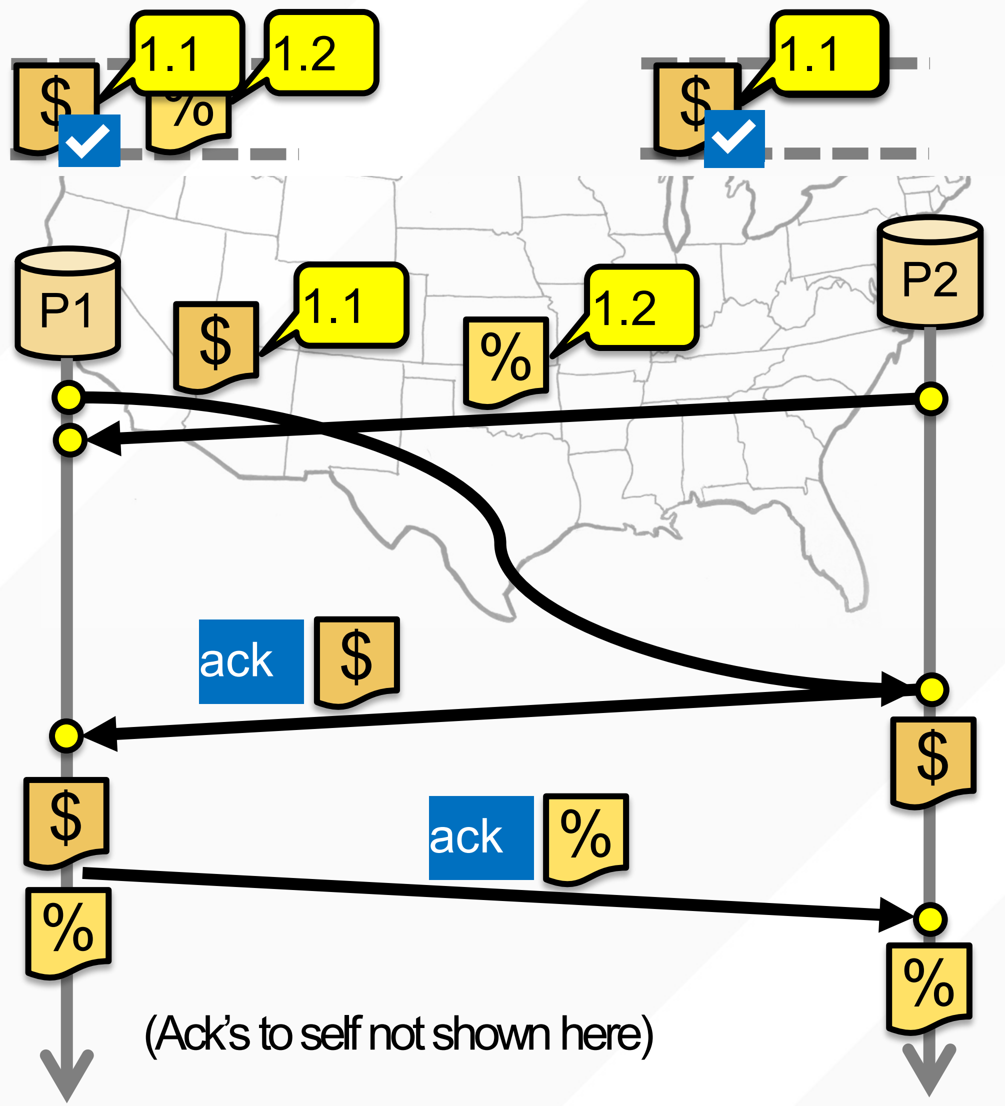
1. On **receiving** an event from **client**, broadcast to others (including yourself)

2. On **receiving or processing** an **event:**
   a) Add it to your local queue
   b) Broadcast an ***acknowledgement message*** to every process (including yourself) **only from head of queue**

3. When you **receive** an **acknowledgement:**
   - Mark corresponding event ***acknowledged*** in your queue

4. **Remove and process** events **<u>everyone</u>** has ack'ed from **<u>head</u>** of queue

TOTALLY-ORDERED MULTICAST



LIMITATIONS OF TOM

- *Does totally-ordered multicast solve the problem of multi-site replication in general?*
- Not by a long shot!

1. Our protocol **assumed:**
   - No **node failures**
   - No **message loss**
   - No **message corruption**
2. All to all communication **does not scale**
3. **Waits forever** for message delays **(performance?)**

PROS AND CONS OF TOTALLY-ORDERED MULTICAST

- Pro: Ensure updates to replicas occur in *same order at all replicas*
- Con: Can't handle packet loss or server failures
- Also assumes that all locations should be exact copies of each other
  - Examples where that isn't true? What about multiple banks?

SCENARIO: MULTI-SITE TRANSACTIONS

- Pay your friend back from a trip to the movies
- Need to:
  - Deduct $10 from your account (at Chase Bank)
  - Deposit $10 into your friend’s account (at Wells Fargo bank)
- Would totally ordered multicast work?
  - What invariants do you need to check/ensure for this to work?
  - Needs application-layer knowledge (network level not enough)

Outline

1. Invariants: Safety and liveness
2. Two-phase commit
3. Two-phase commit failure scenarios

REASONING ABOUT FAULT TOLERANCE

- This is hard!
  - How do we design fault-tolerant systems?
  - How do we know if we're successful?
- Often use "properties" that hold true for every possible execution
- We focus on **safety** and **liveness** properties

SAFETY

- "Bad things" don't happen
  - No stopped or deadlocked states
  - No error states
- Examples
  - Mutual exclusion: two processes can't be in a critical section at the same time
  - Bounded overtaking: if process 1 wants to enter a critical section, process 2 can enter at most once before process 1

LIVENESS

- “Good things” happen
  - …eventually
- Examples
  - Starvation freedom: process 1 can eventually enter a critical section as long as process 2 terminates
  - Eventual consistency: if a value in an application doesn’t change, two servers will eventually agree on its value
    - We’ll revisit this when we talk about *Quorum Replication*

OFTEN A TRADEOFF

- “Good” and “bad” are application-specific
- Safety is very important in banking transactions
  - May take some time to confirm a transaction
- Liveness is very important in social networking sites
  - See updates right away (what about the “friendship problem”?)

Outline

1. Invariants: Safety and liveness
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MOTIVATION: SENDING MONEY

```
send_money(A, B, amount) {
   Begin_Transaction();
   if (A.balance - amount >= 0) {
    A.balance = A.balance - amount;
    B.balance = B.balance + amount;
    Commit_Transaction();
   } else {
    Abort_Transaction();
   }
}
```

SINGLE-SERVER: ACID

- **Atomicity**: all parts of the transaction execute or none (A's decreases and B's balance increases)
- **Consistency**: the transaction only commits if it preserves invariants (A's balance never goes below 0)
- **Isolation**: the transaction executes as if it executed by itself (even if C is accessing A's account, that will not interfere with this transaction)
- **Durability**: the transaction's effects are not lost after it executes (updates to the balances will remain forever)

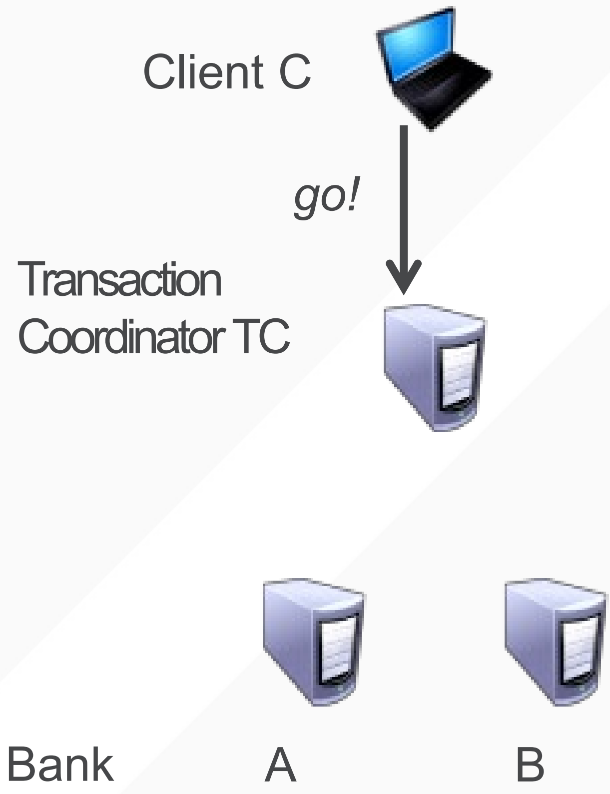
DISTRIBUTED TRANSACTIONS?

- Partition databases across multiple machines for scalability (A and B might not share a server)
- A transaction might touch more than one partition
- How do we guarantee that all of the partitions commit the transactions or none commit the transactions?

TWO-PHASE COMMIT (2PC)

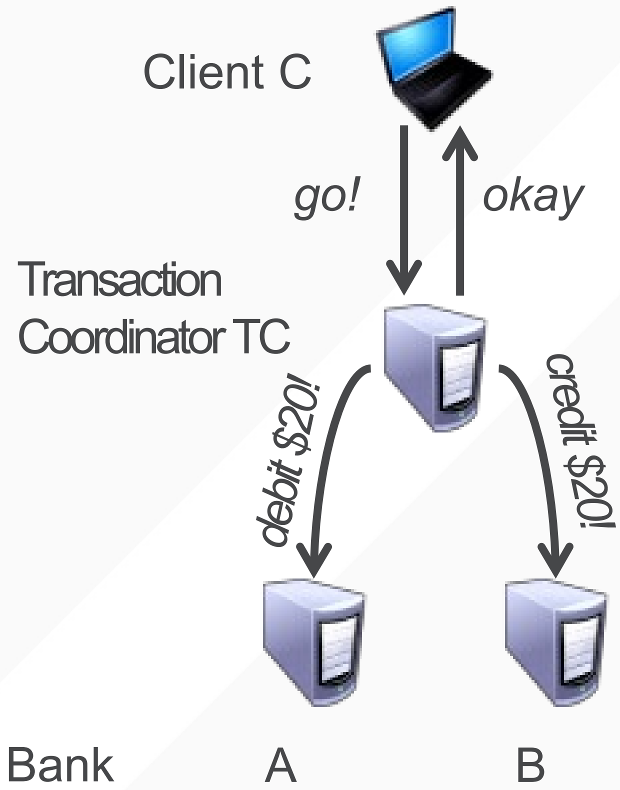
- **Goal:** General purpose, distributed agreement on some action, with failures
  - Different entities play different roles in the action
- **Running example:** Transfer money from A to B
  - Debit at A, credit at B, tell the client "okay"
  - Require **both** banks to do it, or **neither**
  - Require that **one bank never act alone**

STRAW MAN PROTOCOL



1. **C → TC:** *“go!”*

STRAW MAN PROTOCOL



1. **C → TC**: *“go!”*

2. **TC → A**: *“debit $20!”*

   TC → B: *“credit $20!”*

   TC → C: *“okay”*

- **A, B** perform actions on receipt of messages

REASONING ABOUT THE STRAW MAN PROTOCOL

What could **possibly** go wrong?

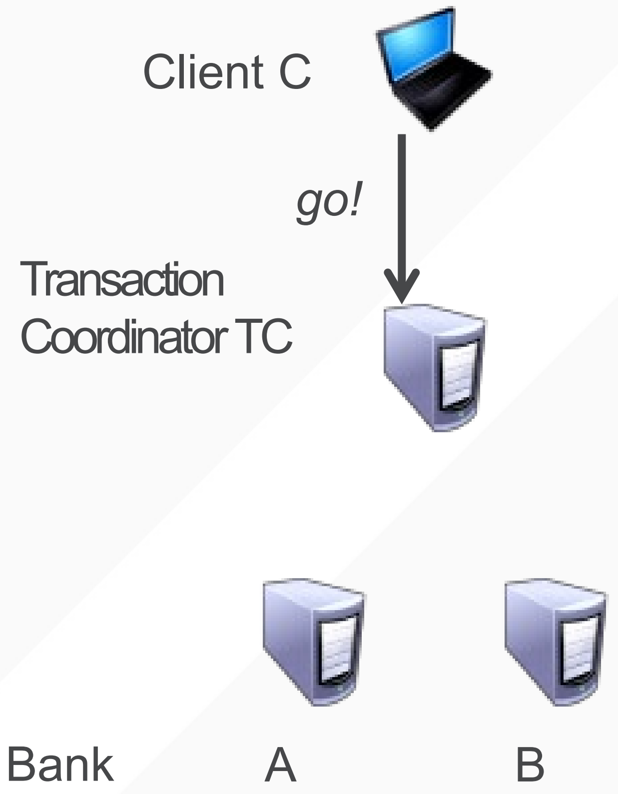
1. Not enough money in **A's** bank account?
2. **B's** bank account no longer exists?
3. **A** or **B** **crashes** before receiving message?
4. The best-effort network to **B** **fails**?
5. **TC** **crashes** after it sends *debit* to **A** but before sending to **B**?

SAFETY VERSUS LIVENESS

- Note that **TC**, **A**, and **B** each have a notion of committing
- We want two properties:

1. Safety
   - If **one commits, no one aborts**
   - If **one aborts, no one commits**
2. Liveness
   - If **no failures** and **A** and **B** can commit, **action commits**
   - If **failures,** reach a conclusion ASAP

A *CORRECT* ATOMIC COMMIT PROTOCOL



1. C → TC: *"go!"*

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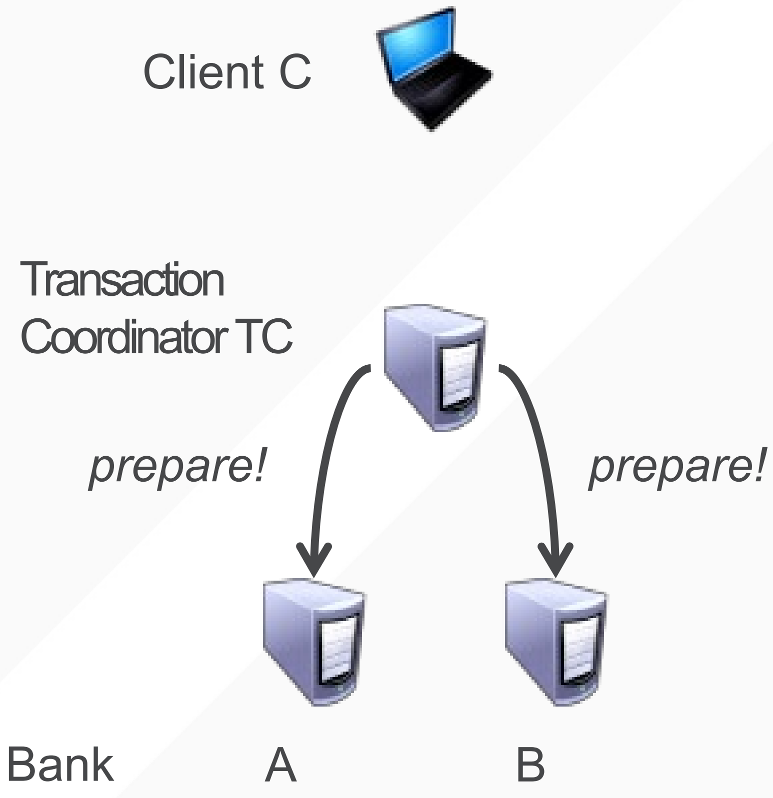

1. **C → TC:** *"go!"*

2. **TC → A, B:** *"prepare!"*

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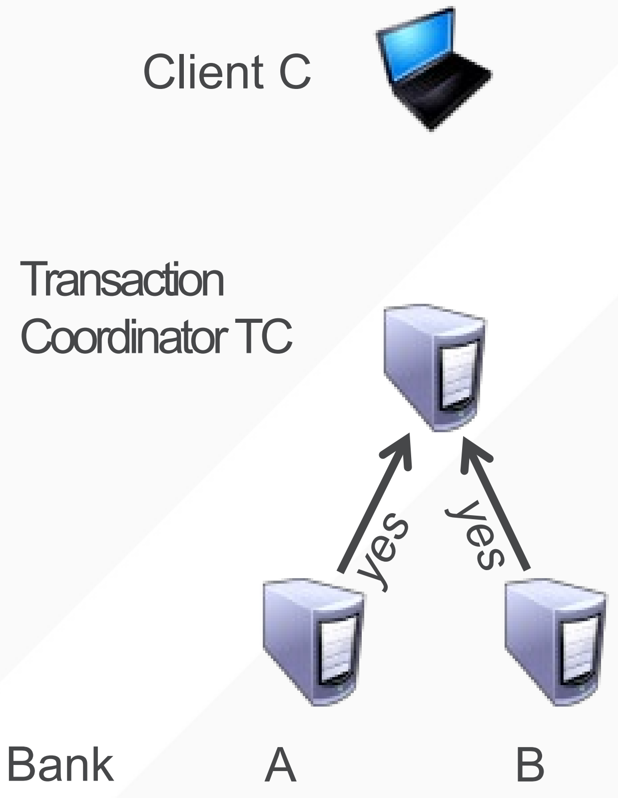

1. **C → TC:** *"go!"*

2. **TC → A, B:** *"prepare!"*

3. **A, B → P:** *"yes"* or *"no"*

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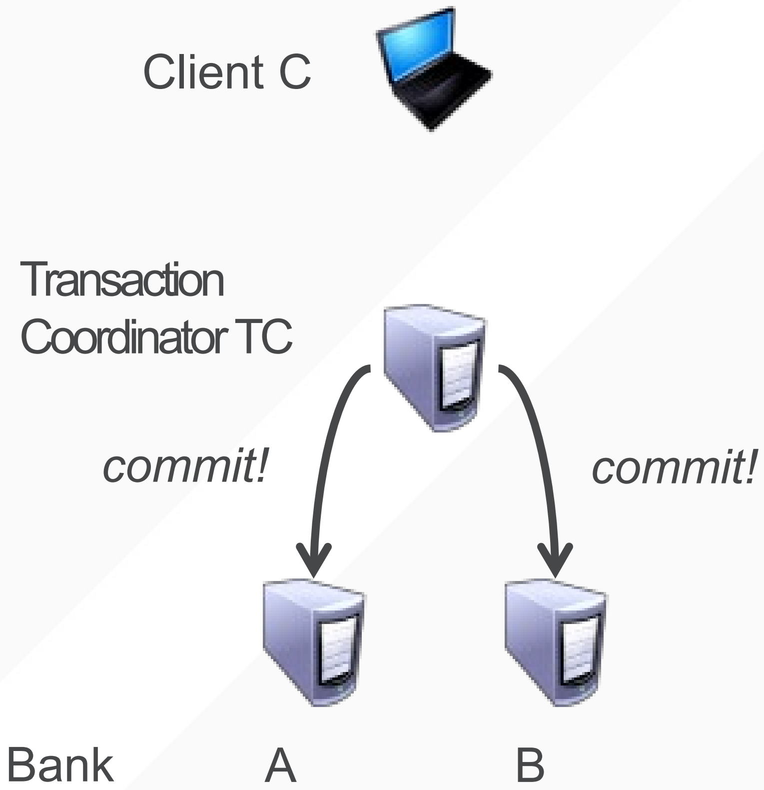
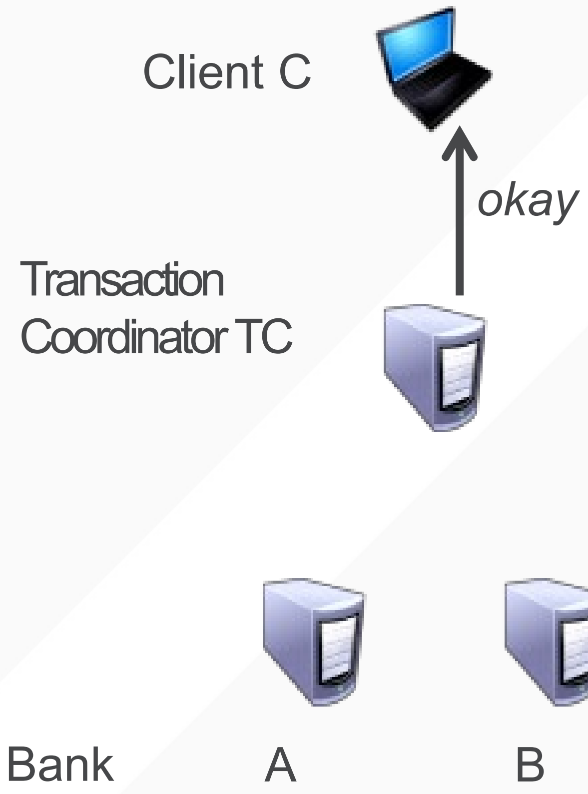


1. **C → TC:** *"go!"*
2. **TC → A, B:** *"prepare!"*
3. **A, B → P:** *"yes"* or *"no"*
4. **TC → A, B:** *"commit!"* or *"abort!"*
   - **TC** sends ***commit*** if **both** say *yes*
   - **TC** sends ***abort*** if **either** say *no*

A *CORRECT* ATOMIC COMMIT PROTOCOL



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2. **TC → A, B:** *"prepare!"*
3. **A, B → P:** *"yes"* or *"no"*
4. **TC → A, B:** *"commit!"* or *"abort!"*
   - **TC** sends ***commit*** if **both** say *yes*
   - **TC** sends ***abort*** if **either** say *no*
5. **TC → C:** *"okay" or "failed"*

- **A, B** commit on receipt of commit message

REASONING ABOUT ATOMIC COMMIT

- *Why is this correct?*
  - Neither can commit unless both agreed to commit
- *What about performance?*
  1. **Timeout:** I'm up, but didn't receive a message I expected
     - Maybe other node crashed, maybe network broken
  2. **Reboot:** Node crashed, is rebooting, must clean up

TIMEOUTS IN ATOMIC COMMIT

Where do hosts **wait** for messages?

1. **TC** waits for "yes" or "no" from **A** and **B**
   - **TC** hasn't yet sent any commit messages, so can **safely abort** after a timeout
   - But this is **conservative:** might be network problem
     - We've preserved correctness, sacrificed performance
2. **A** and **B** wait for "commit" or "abort" from **TC**
   - If it sent a *no*, it can **safely abort** *(why?)*
   - If it sent a *yes*, can it unilaterally abort?
   - Can it unilaterally commit?
   - A, B could wait forever, but there is an alternative…

SERVER TERMINATION PROTOCOL

- Consider Server **B** (Server **A** case is symmetric) waiting for *commit* or *abort* from **TC**
  - Assume **B** voted *yes* (else, unilateral abort possible)
- **B → A:** “status?” **A** then replies back to **B.** Four cases:
  - (No reply from **A**): no decision, **B** waits for **TC**
  - Server **A** received commit or abort from **TC:** Agree with the **TC’s** decision
  - Server **A** hasn’t voted yet or voted *no:* both **abort**
    - **TC** can’t have decided to commit
  - Server **A** voted *yes:* both must **wait** for the **TC**
    - **TC** decided to **commit** if both replies received
    - **TC** decided to **abort** if it timed out

REASONING ABOUT THE SERVER TERMINATION PROTOCOL

- *What are the liveness and safety properties?*
  - **Safety**: if servers don't crash, all processes will reach the same decision
  - **Liveness**: if failures are eventually repaired, then every participant will eventually reach a decision
- Can resolve **some** timeout situations with guaranteed correctness
- Sometimes however **A** and **B** must block
  - Due to failure of the **TC** or network to the **TC**
- But what will happen if **TC, A,** or **B** **crash and reboot?**

HOW TO HANDLE CRASH AND REBOOT?

- Can’t back out of commit if already decided
  - **TC** crashes just after sending *“commit!”*
  - **A** or **B** crash just after sending *“yes”*
- If all nodes knew their state before crash, we could use the termination protocol…
  - Use **write-ahead log** to record *“commit!” and “yes”* to disk

DURABILITY ACROSS REBOOTS

FSYNC(2) Linux Programmer's Manual FSYNC(2)

NAME top

fsync, fdatasync - synchronize a file's in-core state with storage device

SYNOPSIS top

```
#include <unistd.h>

int fsync(int fd);

int fdatasync(int fd);
```

Feature Test Macro Requirements for glibc (see feature_test_macros(7)):

```
fsync():
    Glibc 2.16 and later:
        No feature test macros need be defined
    Glibc up to and including 2.15:
        _BSD_SOURCE || _XOPEN_SOURCE
            || /* since glibc 2.8: */ _POSIX_C_SOURCE >= 200112L
fdatasync():
    _POSIX_C_SOURCE >= 199309L || _XOPEN_SOURCE >= 500
```

RECOVERY PROTOCOL WITH NON-VOLATILE STATE

- If everyone rebooted and is reachable, TC can just check for **commit** record on disk and **resend** action
- **TC:** If no **commit** record on disk, **abort**
  - You didn't send any *"commit!"* messages
- **A, B:** If no **yes** record on disk, **abort**
  - You didn't vote *"yes"* so **TC** couldn't have committed
- A, B: If **yes** record on disk, execute termination protocol
  - This might block

TWO-PHASE COMMIT

- This recovery protocol with non-volatile logging is called ***Two-Phase Commit (2PC)***
- **Safety:** All hosts that decide reach the same decision
  - No commit unless everyone says "yes"
- **Liveness:** If no failures and all say "yes" then commit
  - **But if failures then 2PC might block**
  - **TC must be up to decide**
- **Doesn't tolerate faults well: must wait for repair**

Outline

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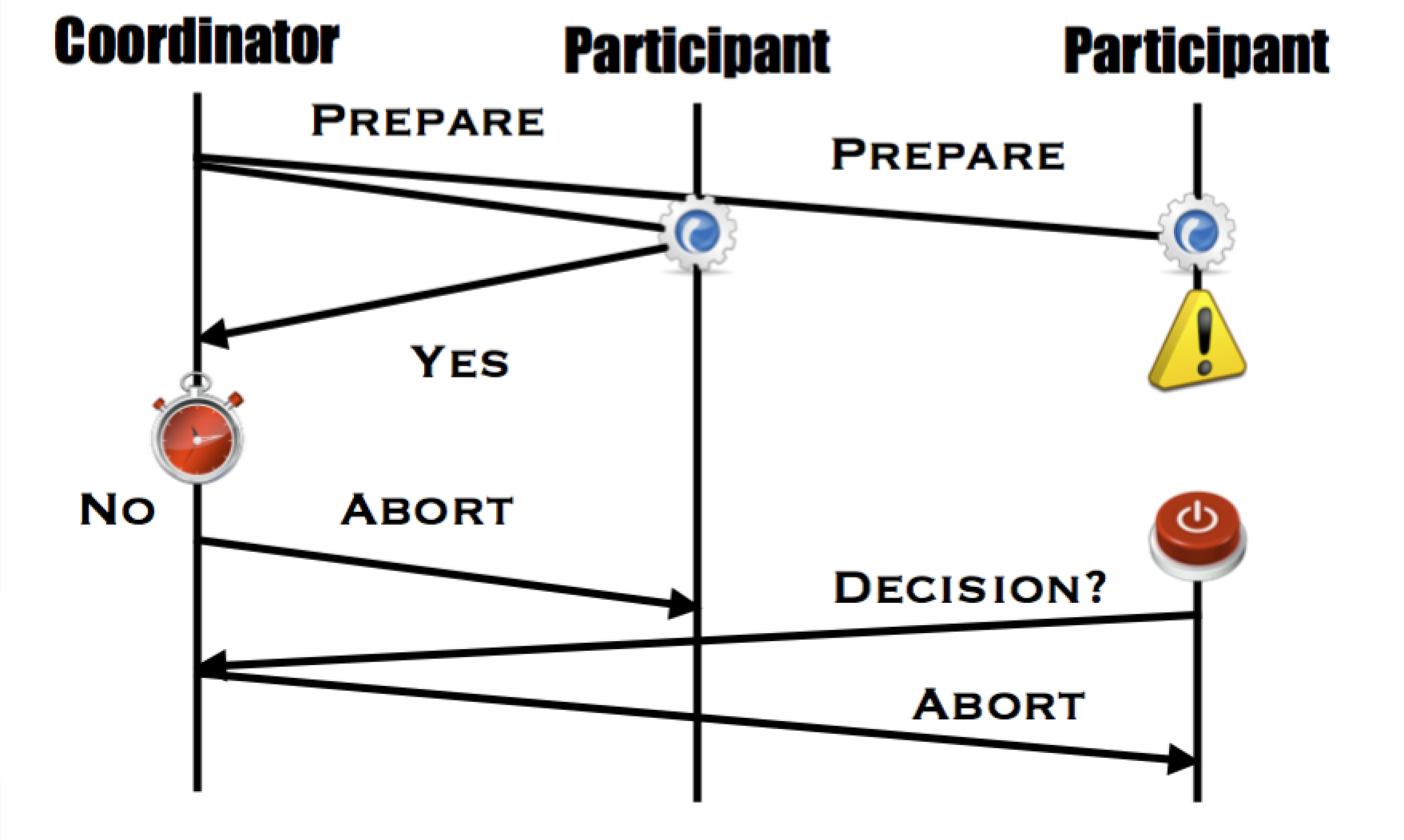
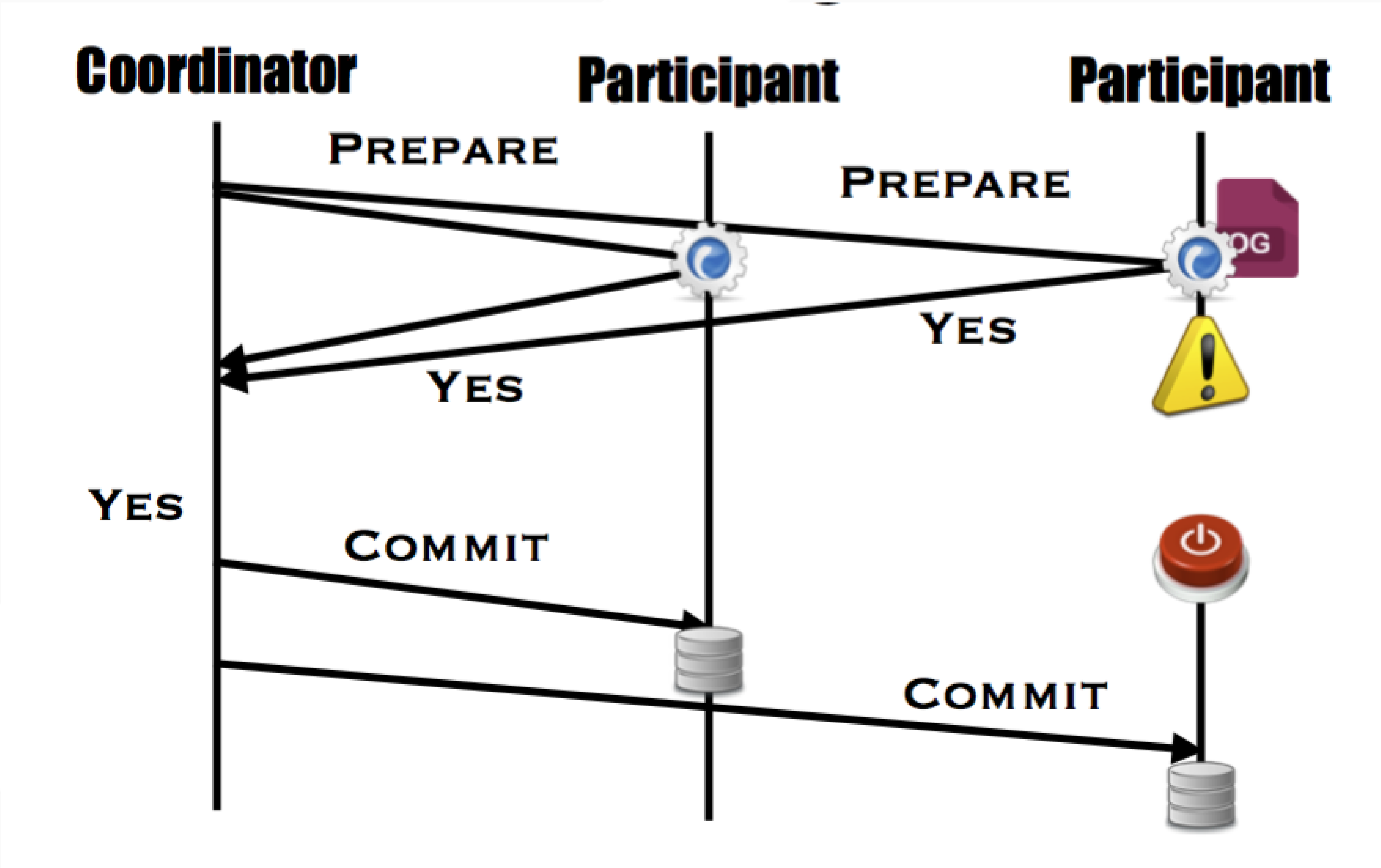
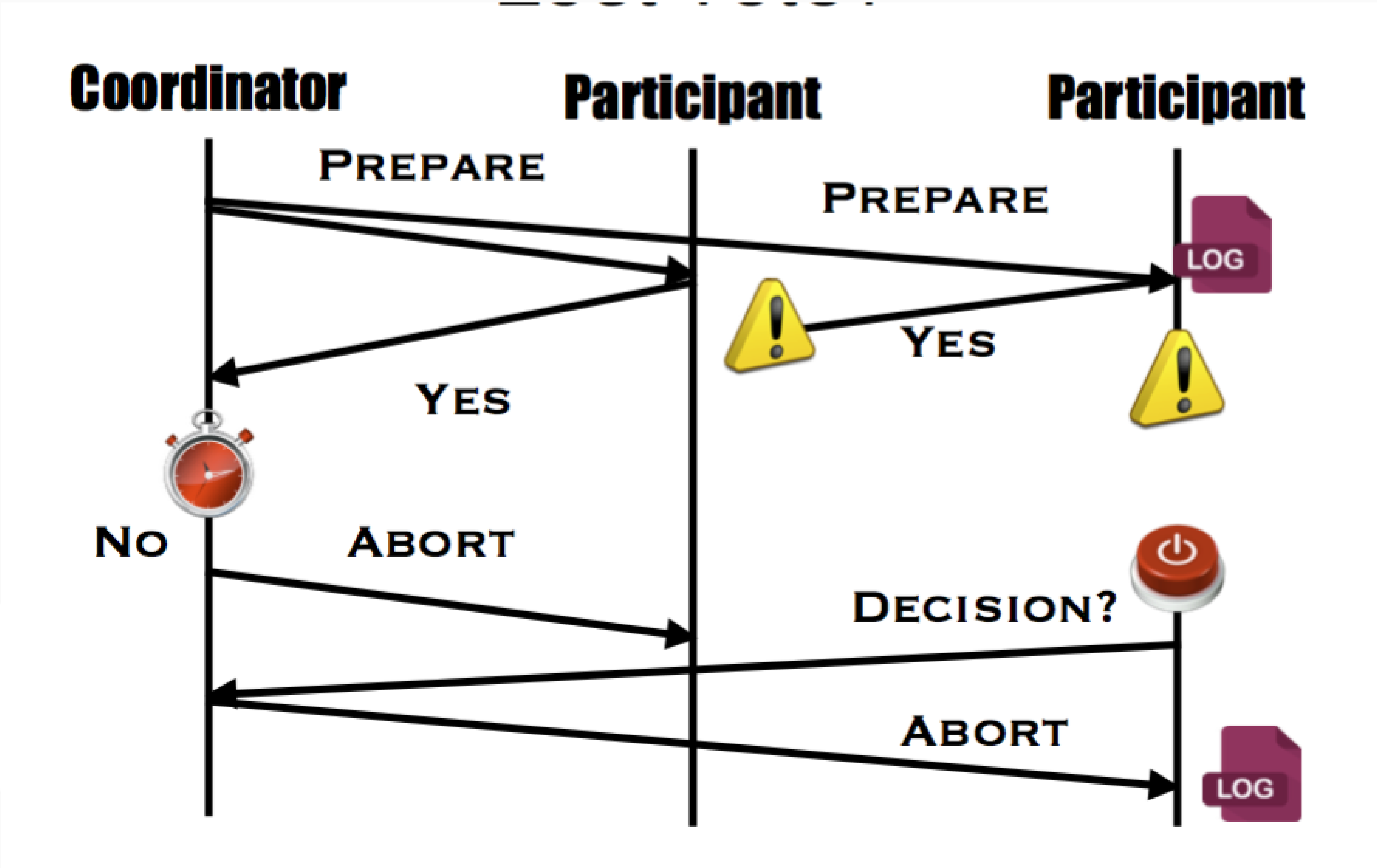
WHAT IF PARTICIPANT FAILS BEFORE SENDING RESPONSE?



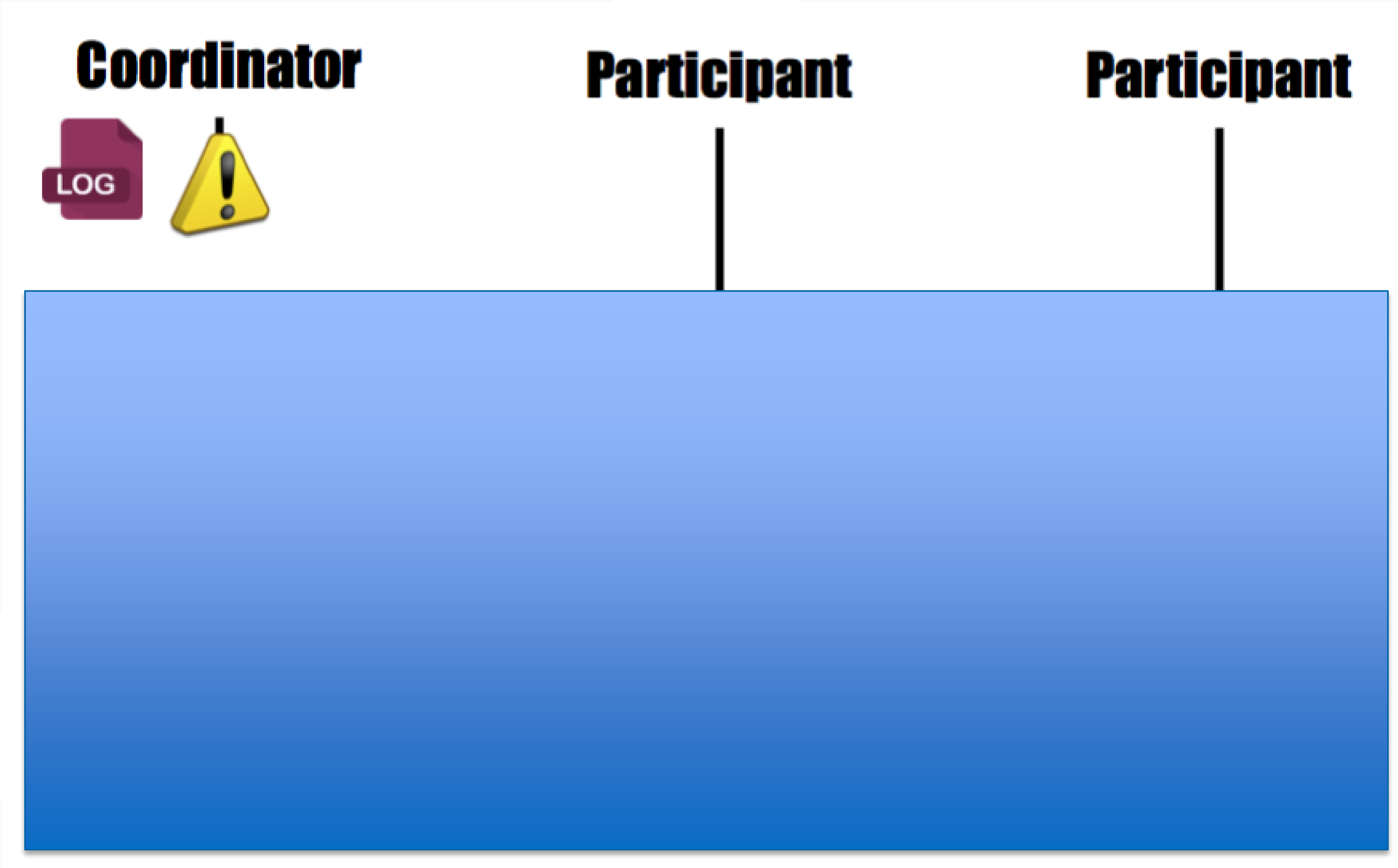
WHAT IF PARTICIPANT FAILS AFTER SENDING VOTE



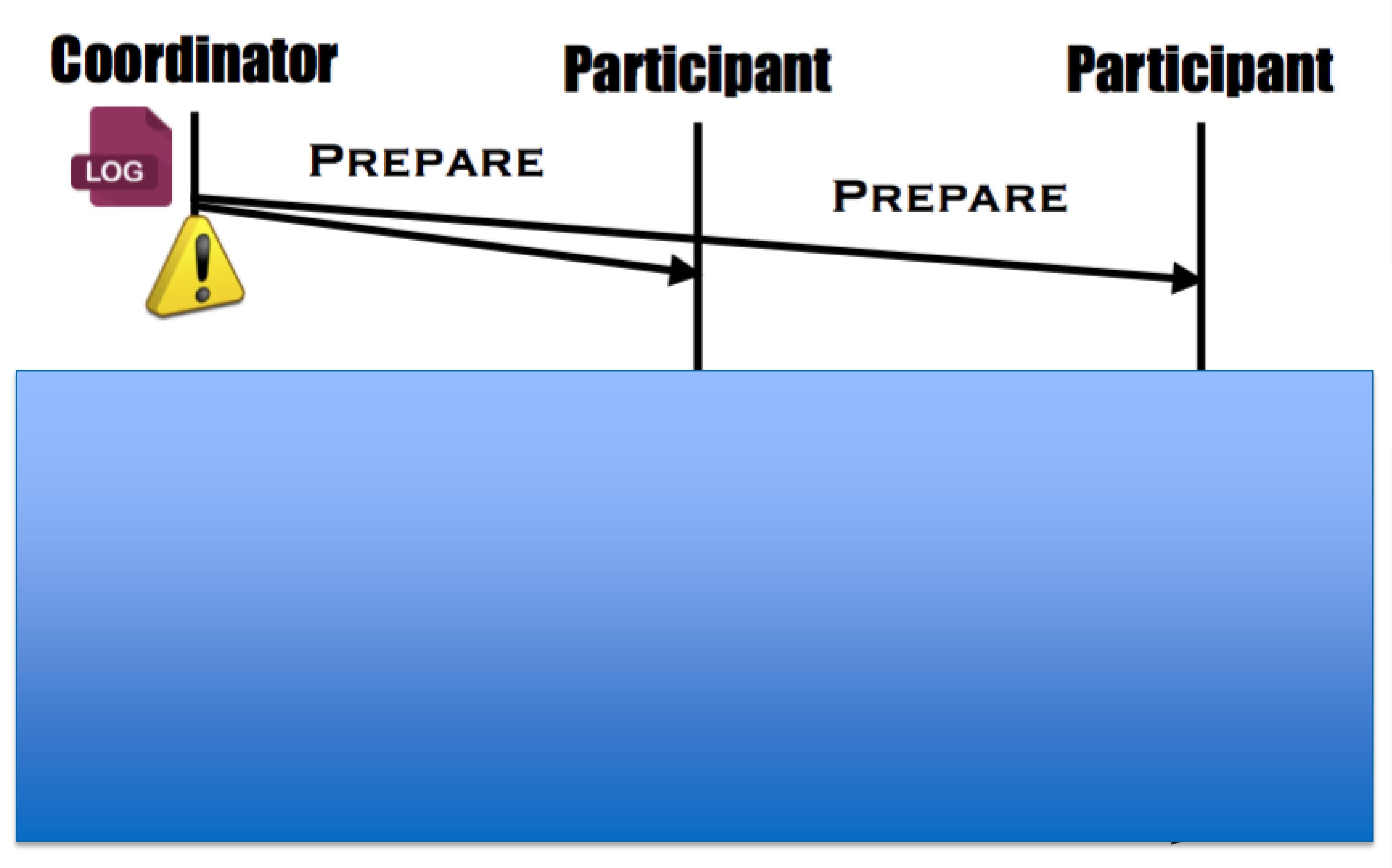
WHAT IF PARTICIPANT LOST A VOTE?



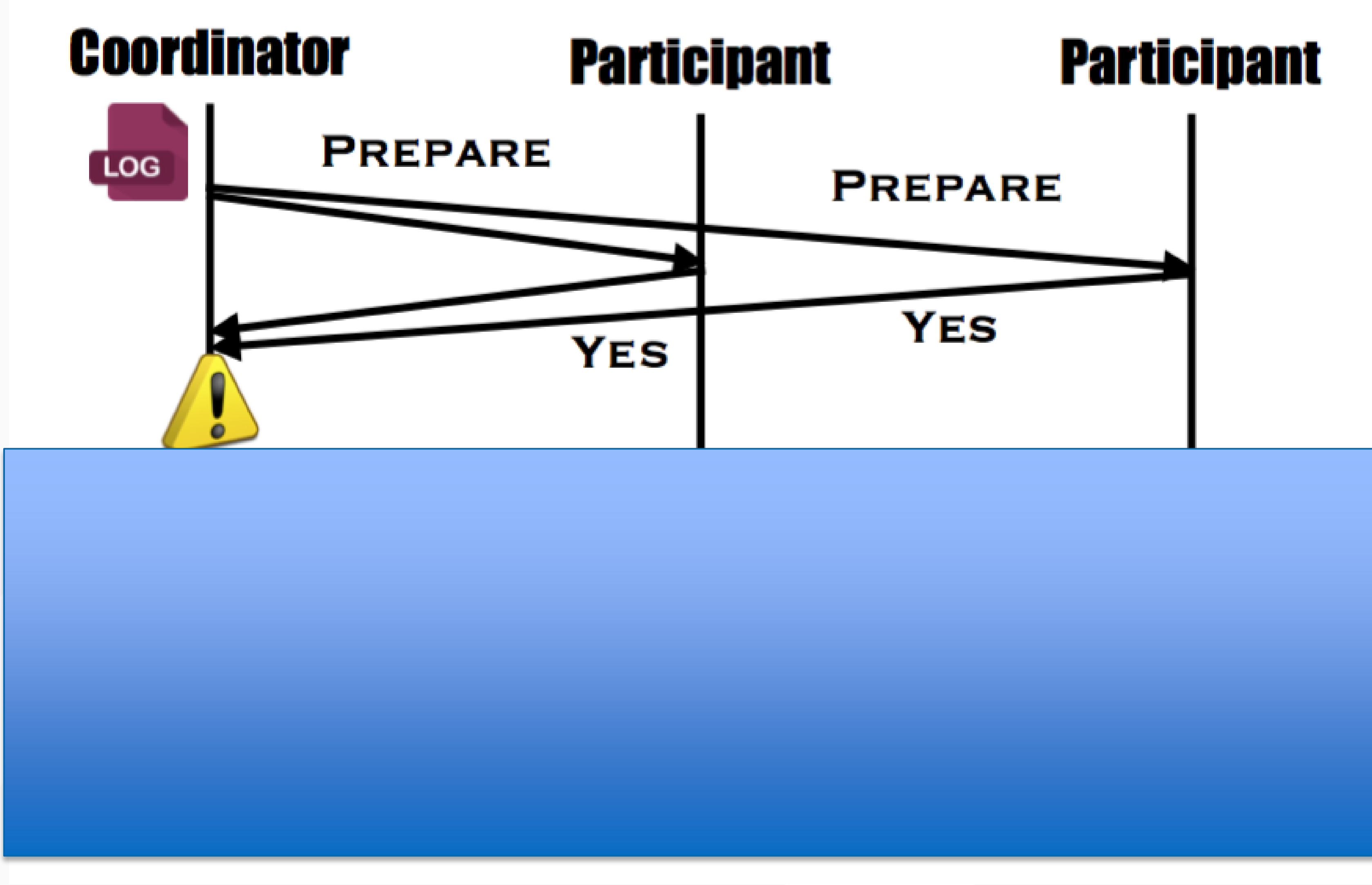
WHAT IF COORDINATOR FAILS BEFORE SENDING PREPARE?



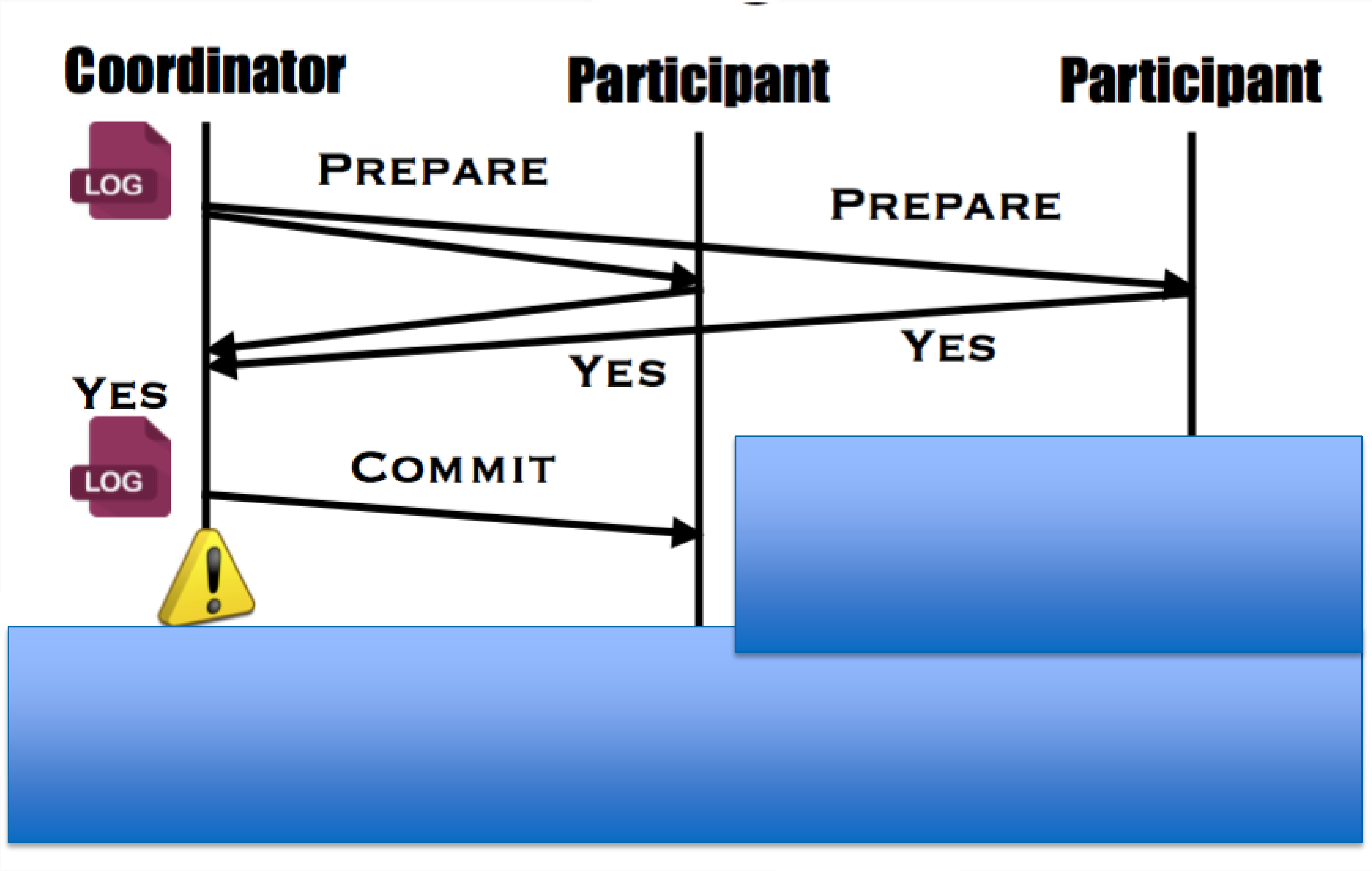
WHAT IF COORDINATOR FAILS AFTER SENDING PREPARE?



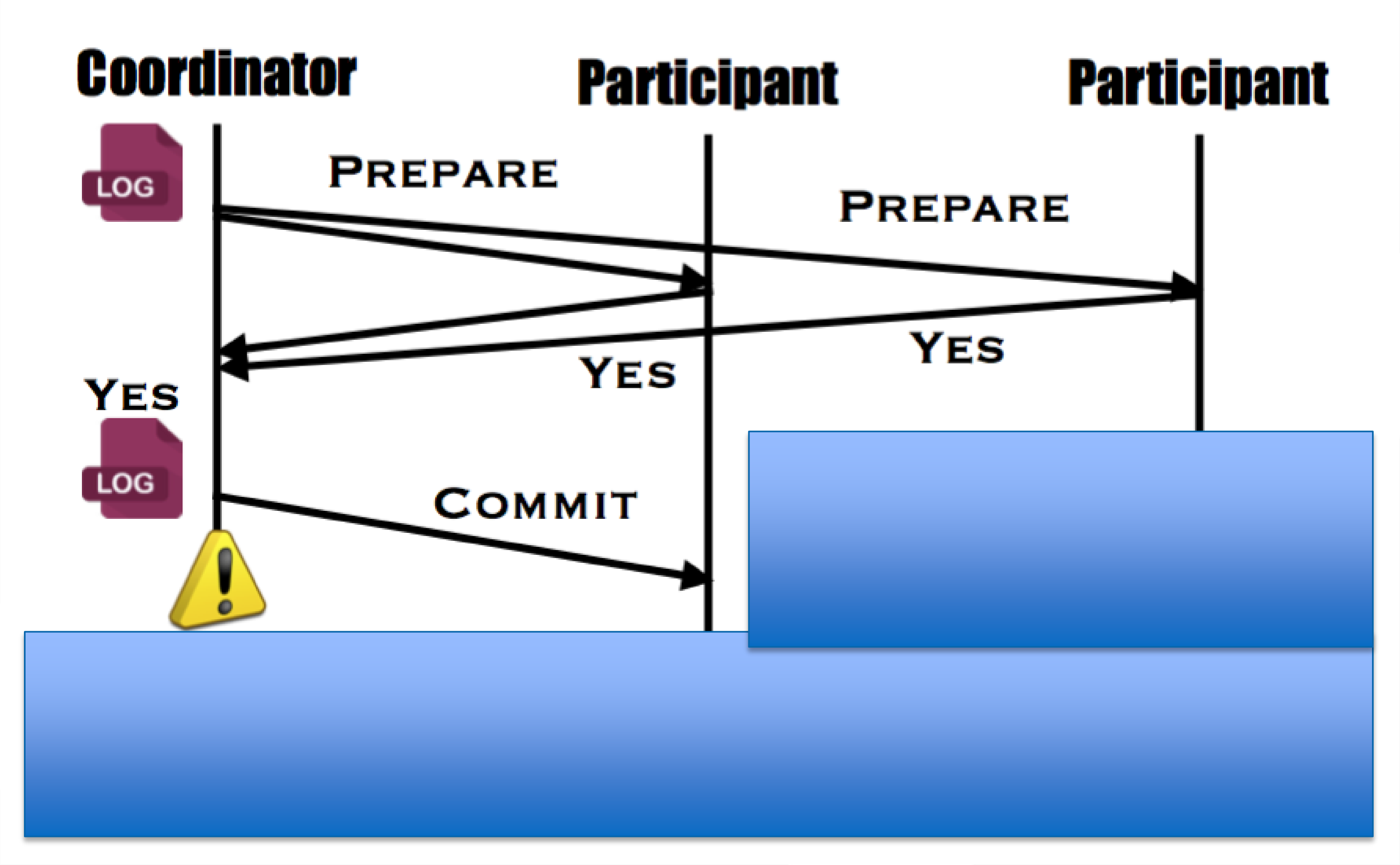
WHAT IF COORDINATOR FAILS AFTER RECEIVING VOTES



WHAT IF COORDINATOR FAILS AFTER SENDING DECISION?



DO WE NEED THE COORDINATOR?



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