Distributed DBMS reliability

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These slides are a modified version of the slides provided with the book

Özsu and Valduriez, *Principles of Distributed Database Systems* (3rd Ed.), 2011

The original version of the slides is available at: extras.springer.com

Outline (distributed DB)

- Introduction (Ch. 1) *
- Distributed Database Design (Ch. 3) *
- Distributed Query Processing (Ch. 6-8) *
- Distributed Transaction Management (Ch. 10-12) *
  - ➡ Introduction to transaction management (Ch. 10) *
  - ➡ Distributed Concurrency Control (Ch. 11) *
  - ➡ **Distributed DBMS Reliability (Ch. 12)** *

* Özsu and Valduriez, *Principles of Distributed Database Systems* (3rd Ed.), 2011

Outline (today)

- Distributed DBMS Reliability (Ch. 12) *
  - ➡ Introduction and local reliability protocols
  - ➡ Distributed reliability protocols
    - ✦ Two-phase commit (2PC) protocol

* Özsu and Valduriez, *Principles of Distributed Database Systems* (3rd Ed.), 2011

Reliability

Problem:

How to maintain

atomicity

durability

properties of transactions

Fundamental Definitions

- Reliability
  - ➞ A measure of success with which a system conforms to some authoritative specification of its behavior
- Availability
  - ➞ The fraction of the time that a system meets its specification
- Failure
  - ➞ The deviation of a system from the behavior that is described in its specification

Types of Failures

- Transaction failures
  - ➠ Transaction aborts (unilaterally or due to deadlock)
- System (site) failures
  - ➠ Failure of processor, main memory, power supply, …
  - ➠ Main memory contents are lost, but secondary storage contents are safe
  - ➠ Partial (some sites) vs. total (all sites) failure
- Media failures
  - ➠ Failure of secondary storage devices such that the stored data is lost
  - ➠ Head crash/controller failure (?)
  - ➠ Permanent data loss (secondary, resilient, stable memory – hard disk)
- Communication failures
  - ➠ Lost/undeliverable messages
  - ➠ Network partitioning

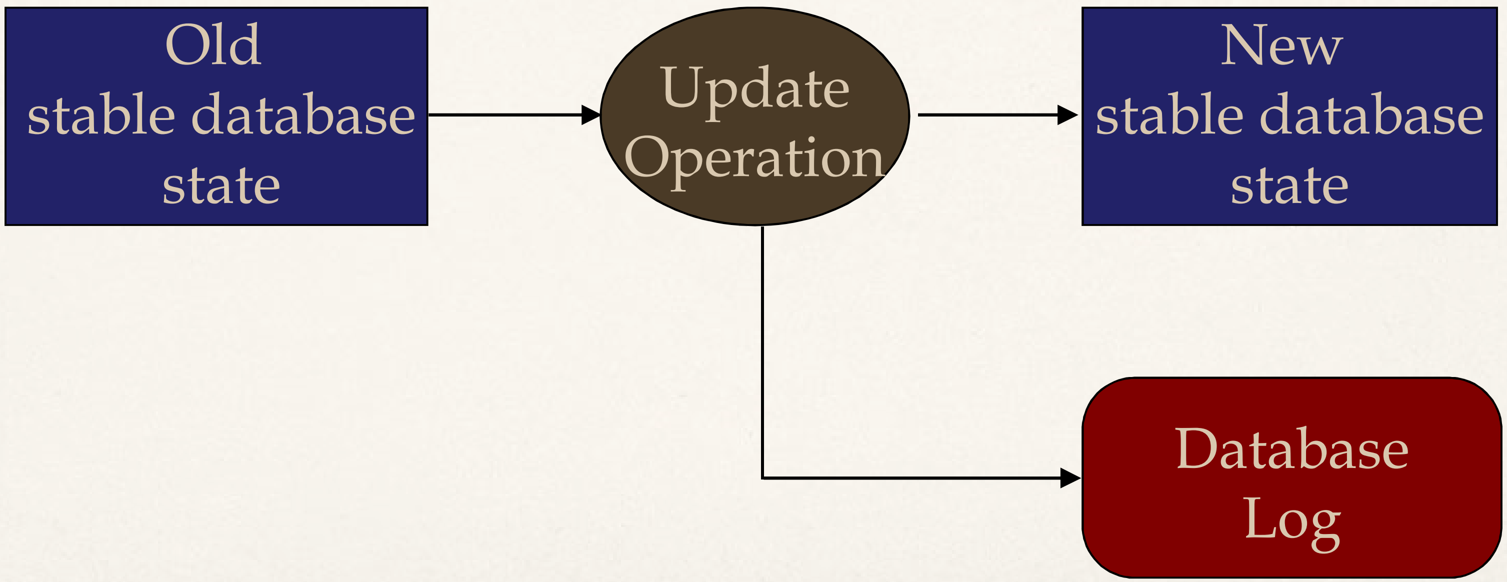
Update Strategies

- In-place update
  - Each update causes a change in one or more data values in the database
  - More efficient, more difficult to undo
- Out-of-place update
  - Each update causes the new value(s) of data item(s) to be stored separately from the old value(s)
  - Less efficient, easy to undo

In-Place Update Recovery Information

Database Log

Every action of a transaction must not only perform the action, but must also write a *log* record to an append-only file.



Logging

The log contains information used by the recovery process to restore the consistency of a system. This information may include

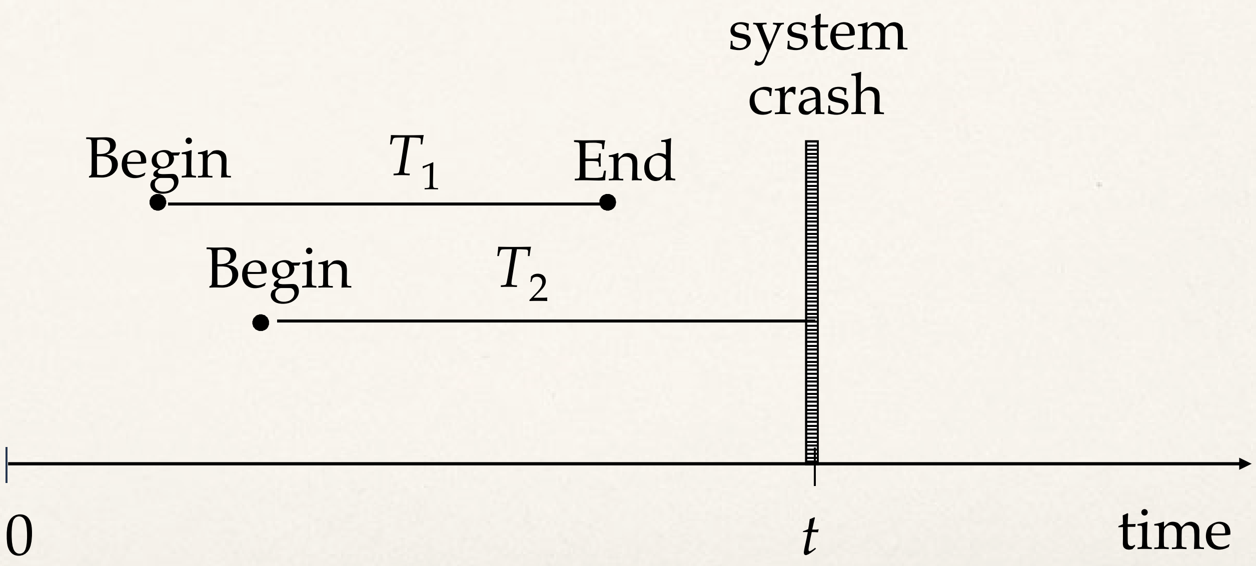
- transaction identifier
- type of operation (action)
- items accessed by the transaction to perform the action
- old value (state) of item (before image)
- new value (state) of item (after image)

  …

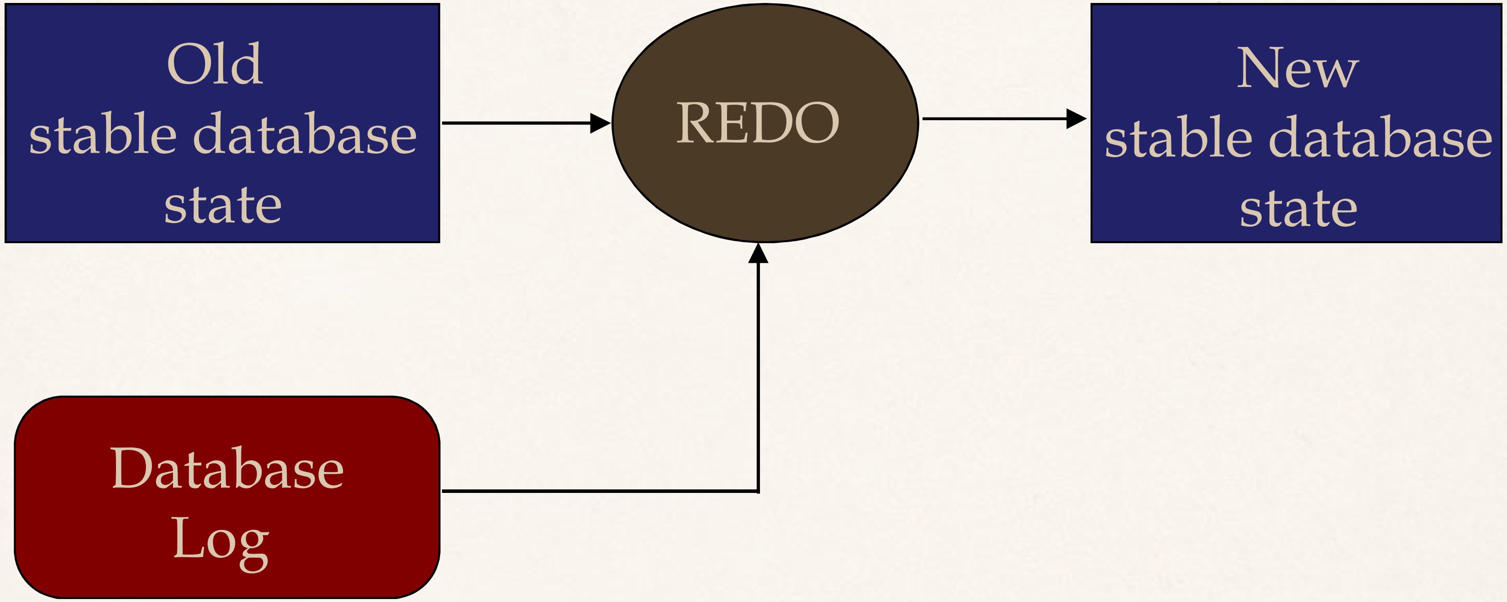
Why Logging?

Upon recovery:

- all of T_1's effects should be reflected in the database (REDO if necessary due to a failure)
- none of T_2's effects should be reflected in the database (UNDO if necessary)

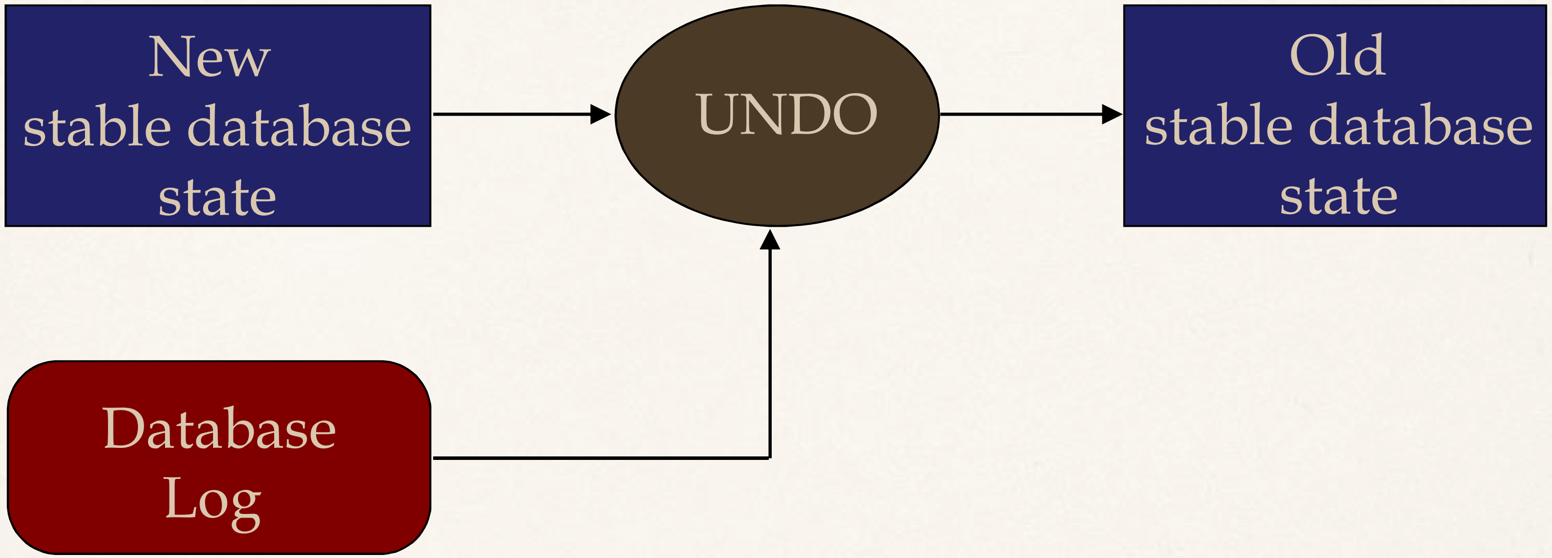


REDO Protocol



- REDO'ing an action means performing it again
- The REDO operation uses the log information
- REDO is needed when effects of a committed transaction were not stored yet in secondary (stable, resilient) memory
  - → sometimes for efficiency reasons storying information to disk (secondary memory) is done at a later time

UNDO Protocol



- UNDO'ing an action means to restore the object to its before image
- The UNDO operation uses the log information
- UNDO is needed when effects of a transaction are stored in secondary (stable, resilient) memory and then an abort occurs
  - → sometimes to free main memory, information is stored to disk (secondary memory) before commit

When to Write Log Records Into Stable Store

Assume a transaction *T* updates a page *P*

- Fortunate case
  - System writes *P* in stable database
  - System updates stable log for this update
  - SYSTEM FAILURE OCCURS!... (before *T* commits)

  We can recover (undo) by restoring *P* to its old state by using the log
- Unfortunate case
  - System writes *P* in stable database
  - SYSTEM FAILURE OCCURS!... (before stable log is updated)

  We cannot recover from this failure because there is no log record to restore the old value.
- Solution: Write-Ahead Log (WAL) protocol

Write–Ahead Log Protocol

- Notice:
  - ➡ If a system crashes before a transaction is committed, then all the operations must be undone. Only need the before images (*undo portion* of the log)
  - ➡ Once a transaction is committed, some of its actions might have to be redone. Need the after images (*redo portion* of the log)
- WAL protocol :
  1. Before a stable database is updated, the undo portion of the log should be written to the stable log
  2. When a transaction commits, the redo portion of the log must be written to stable log prior to the updating of the stable database.

Execution of Commands

Commands to consider:

- begin_transaction
- read
- write
- abort
- commit
- recover

(begin_transaction, read, write) } Independent of execution strategy for LRM

Execution Strategies

- Dependent upon
  - Can the buffer manager (**BM**) decide to write some of the buffer pages being accessed by a transaction into stable storage or does it wait for LRM to instruct it?
    - fix/no-fix decision (*fix* means BM ***cannot*** store the data into disk before commit)

      (***no-fix*** means BM ***can*** store data to disk before commit)
  - Does the LRM force the buffer manager to write certain buffer pages into stable database at the end of a transaction's execution?
    - flush/no-flush decision (***flush*** means BM ***cannot*** wait; it must store data into disk at commit)

      (***no-flush*** means BM ***can*** wait; it can store data into disk at a later time)
- Possible execution strategies:
  - no-fix/no-flush
  - no-fix/flush
  - fix/no-flush
  - fix/flush

No-Fix/No-Flush

- Abort
  - ➡ Buffer manager may have written some of the updated pages into stable database (second memory, disk)
  - ➡ LRM performs transaction undo
- Commit
  - ➡ LRM writes an "end_of_transaction" record into the log
  - ➡ Data not necessarily written into disk
- Recover
  - ➡ For those transactions that have both a "begin_transaction" and an "end_of_transaction" record in the log, a redo is initiated by LRM
  - ➡ For those transactions that only have a "begin_transaction" in the log, an undo is executed by LRM

No-Fix/Flush

- Abort
  - Buffer manager may have written some of the updated pages into stable database (second memory, disk)
  - LRM performs transaction undo
- Commit
  - LRM issues a `flush` command to the buffer manager for all updated pages
    - i.e., data is stored into disk at time of commit
  - LRM writes an "end_of_transaction" record into the log
- Recover
  - No need to perform redo
  - Perform undo

Fix/No-Flush

- Abort
  - ➞ None of the updated pages have been written into stable database
  - ➞ Release the `fixed` pages
- Commit
  - ➞ LRM writes an "end_of_transaction" record into the log
  - ➞ Data not necessarily written into disk
  - ➞ LRM sends an `unfix` command to the buffer manager for all pages that were previously `fixed`
- Recover
  - ➞ Perform redo
  - ➞ No need to perform undo

Fix/Flush

- Abort
  - None of the updated pages have been written into stable database
  - Release the `fixed` pages
- Commit (the following have to be done atomically)
  - LRM issues a `flush` command to the buffer manager for all updated pages
    - i.e., data is stored into disk at time of commit
  - LRM sends an `unfix` command to the buffer manager for all pages that were previously `fixed`
  - LRM writes an "end_of_transaction" record into the log
- Recover
  - No need to do anything

Checkpoints

- Simplifies the task of determining actions (of transactions) that need to be undone or redone when a failure occurs
  - → Avoid scanning the whole log
- A checkpoint identify a consistent state of the DB
- Steps to create a checkpoint:
  1. Write a begin_checkpoint record into the log
  2. Collect the checkpoint data into the stable storage (log and actual DB data)
     - During this phase stop accepting new transactions, complete all currently active ones
  3. Write an end_checkpoint record into the log

Distributed Reliability Protocols

- Commit protocols
  - ➡ How to execute commit command for distributed transactions
  - ➡ Issue: how to ensure atomicity and durability?
- Termination protocols
  - ➡ If a failure occurs, how the remaining operational sites behave
  - ➡ *Non-blocking* : the occurrence of failures should not force the sites to wait until the failure is repaired to terminate the transaction
- Recovery protocols
  - ➡ When a failure occurs, how the sites where the failure occurred behave after they are back on
  - ➡ *Independent* : a failed site can determine the outcome of a transaction without having to obtain remote information.
- Independent recovery $\Rightarrow$ non-blocking termination

Two-Phase Commit (2PC)

- **Coordinator** :The process at the site where the transaction originates and which controls the execution
- **Participant** :The process at the other sites that participate in executing the transaction

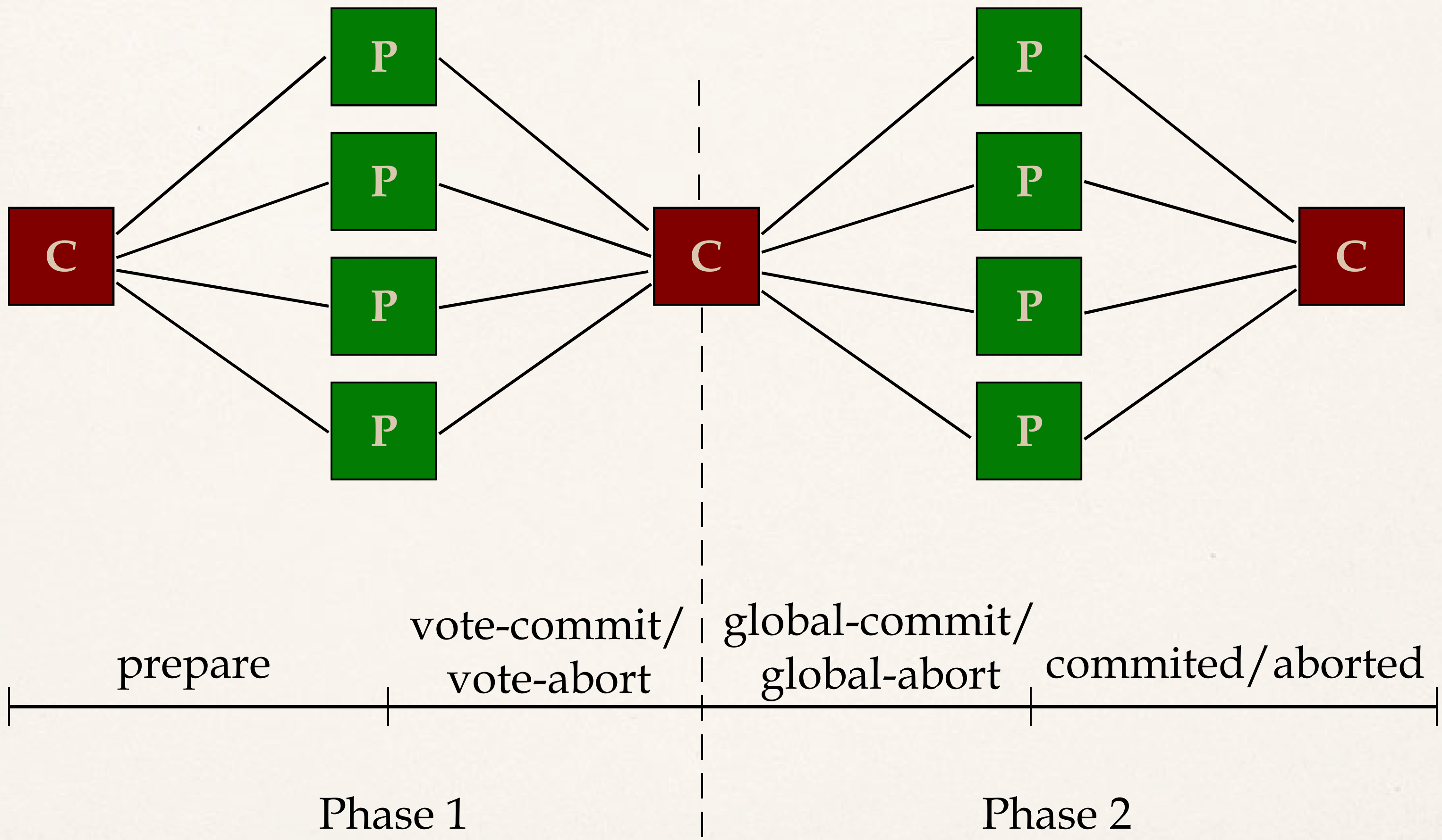
Phase 1 : The coordinator gets the participants ready to commit and collects their reply

Phase 2 : The coordinator decides global-abort/global-commit depending on participants' replies, communicate the decision to them, and waits for ack's

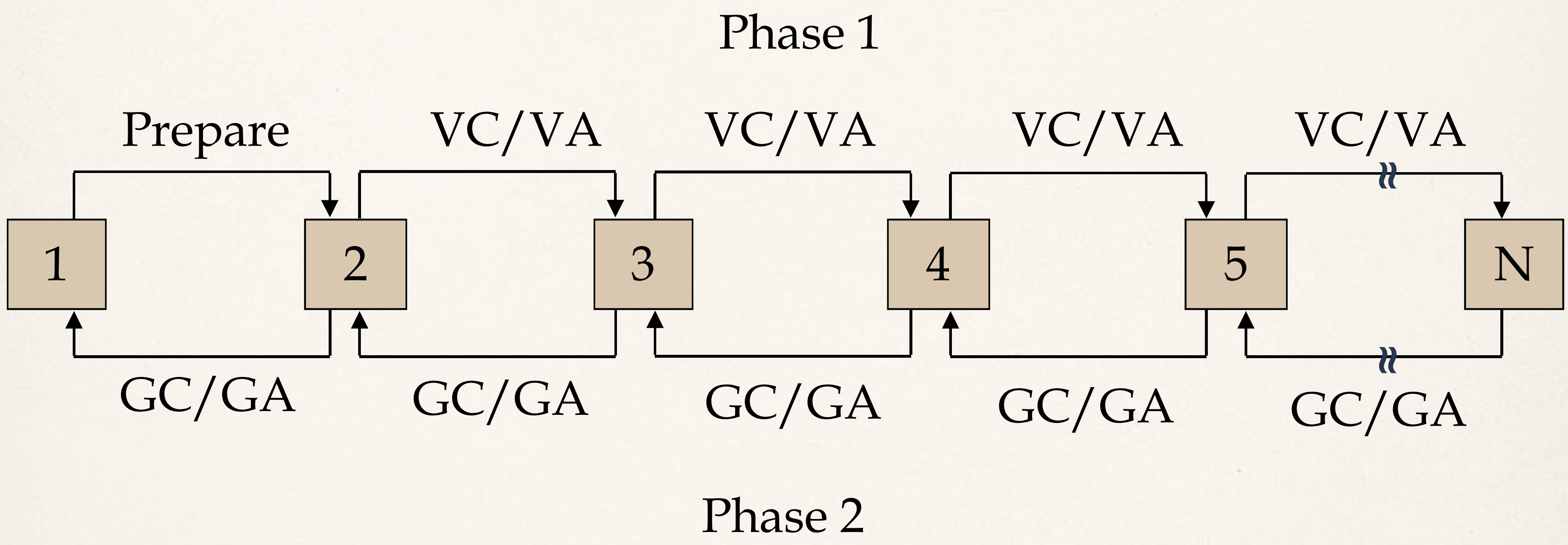
Global Commit Rule:

- The coordinator aborts a transaction if and only if at least one participant votes to abort it
  - Equivalently: The coordinator commits a transaction if and only if all of the participants vote to commit it

Centralized 2PC

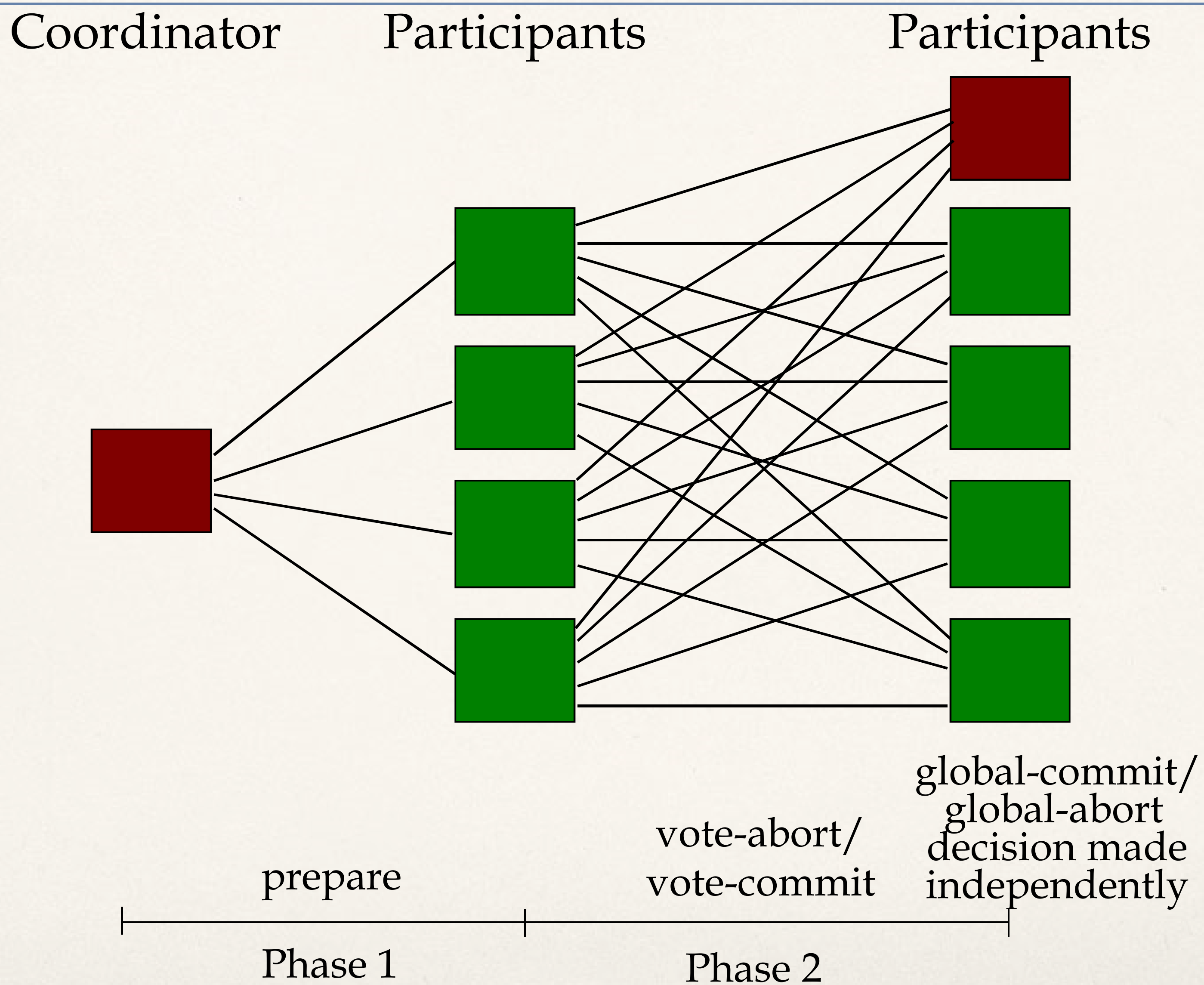


Linear 2PC



VC: Vote-Commit, VA: Vote-Abort, GC: Global-commit, GA: Global-abort

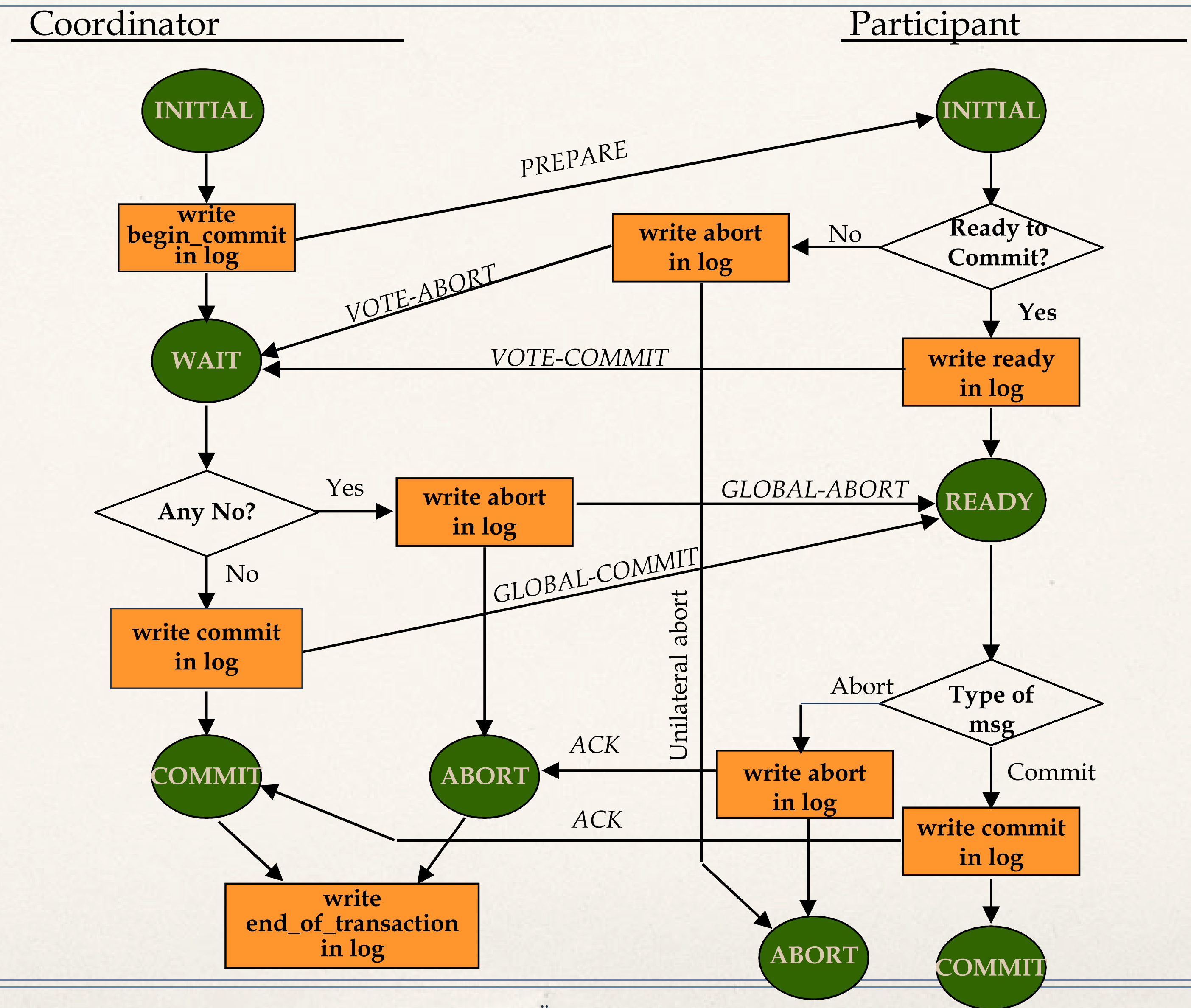
Distributed 2PC



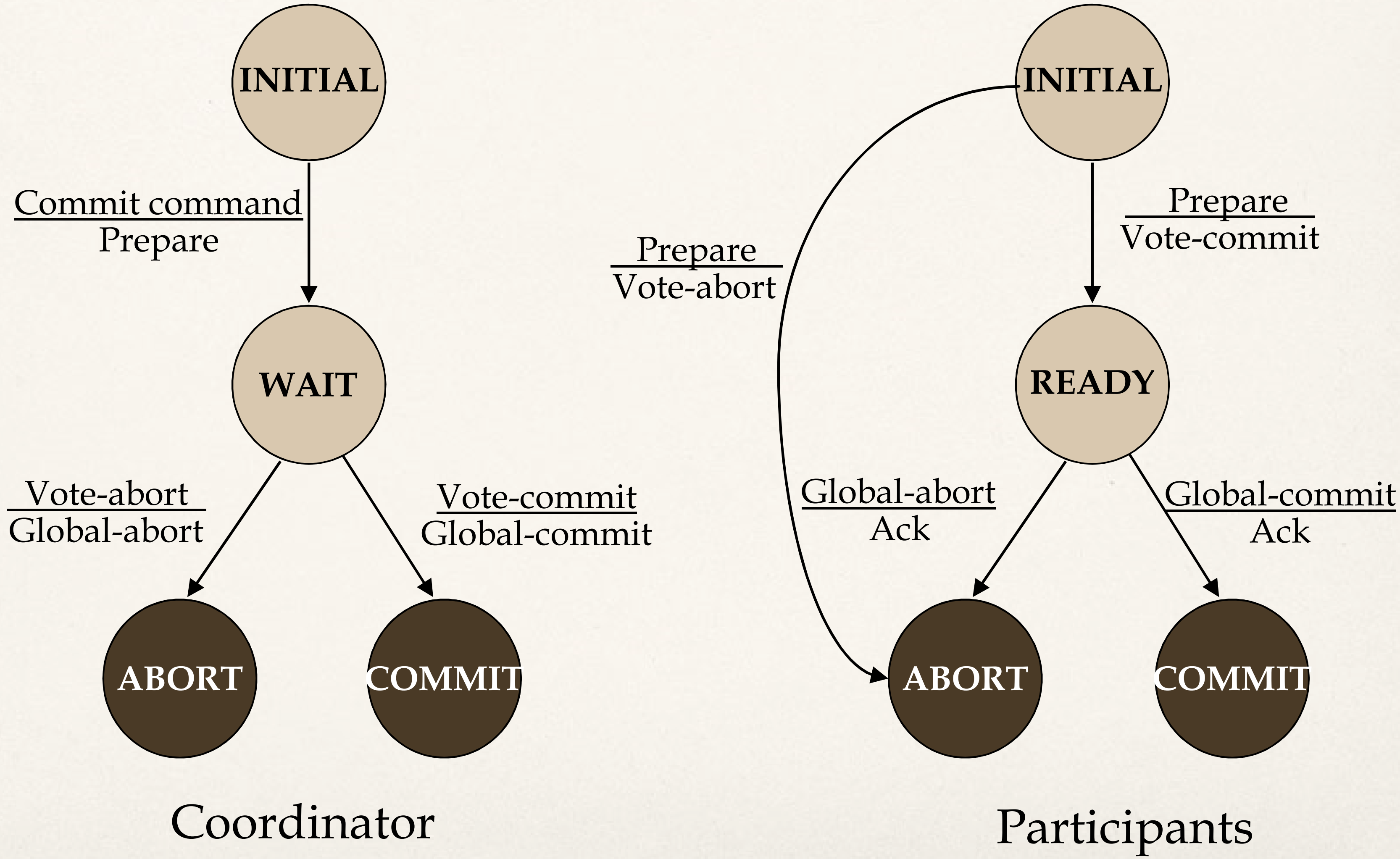
Variations of 2PC

- Presumed abort 2PC and presumed commit 2PC
- Coordinator and participant may assume global-abort or global-commit if they do not get communication
  - ➡ Reduced communication

2PC Protocol Actions

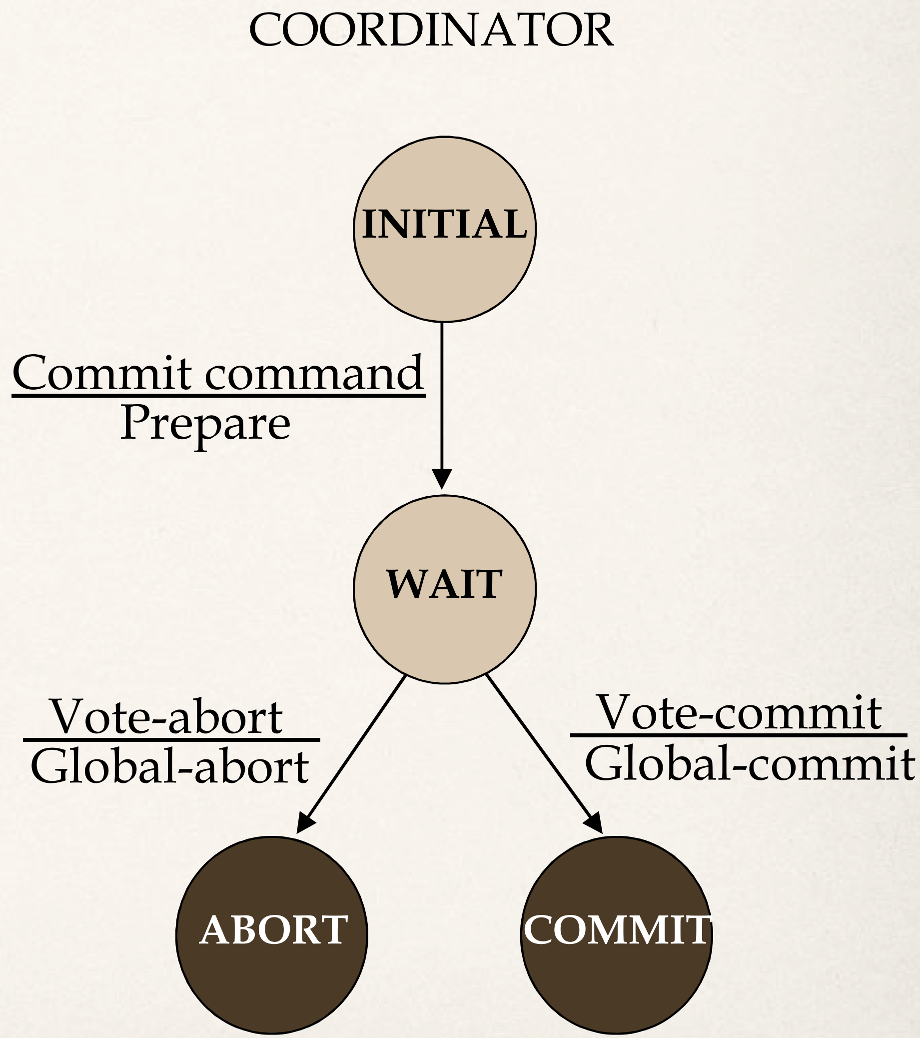


State Transitions in 2PC



Site Failures - 2PC Termination

- Timeout in WAIT
  - Cannot unilaterally commit
  - Can unilaterally abort
- Timeout in ABORT or COMMIT
  - Stay blocked and wait for the acks
  - Repeatedly send "global-commit" or "global-abort" to unresponsive participants

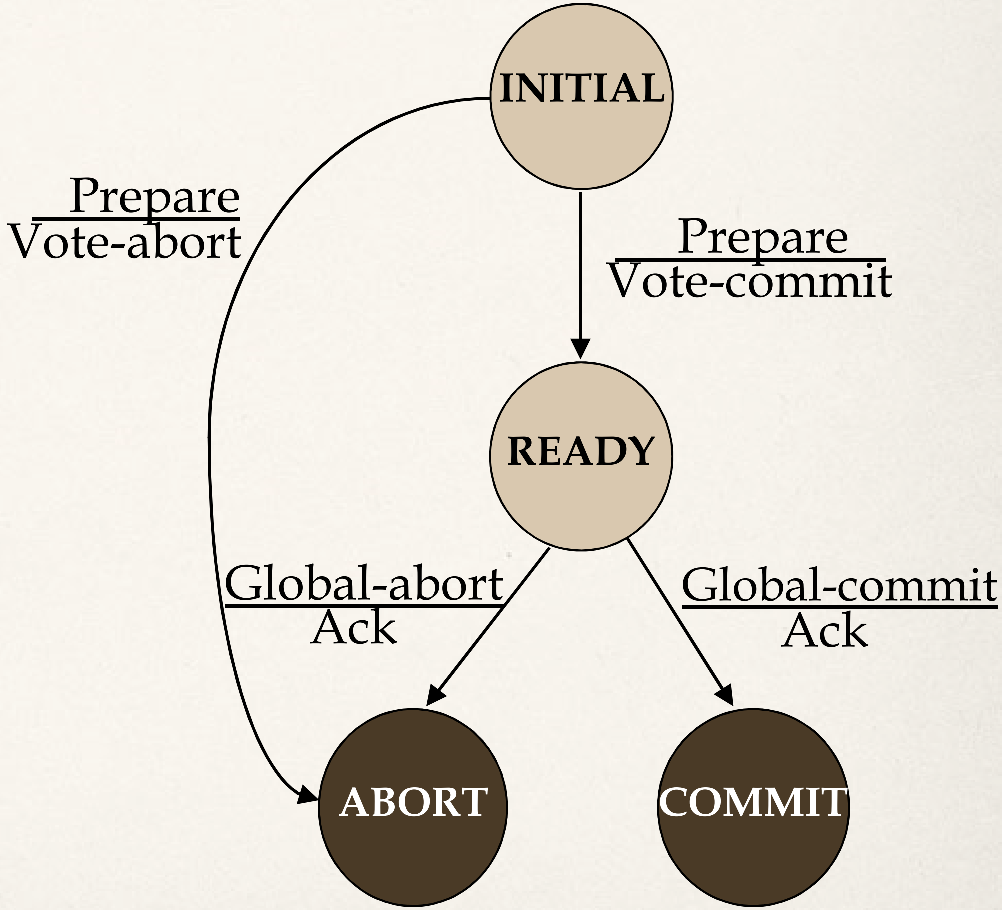


Site Failures - 2PC Termination

- Timeout in INITIAL
  - Coordinator must have failed in INITIAL state
  - Unilaterally abort
- Timeout in READY
  - Stay blocked
  - Repeatedly send "vote-commit" to coordinator

- If participants can communicate, they can resolve blocked situations. Assume P_i timed out in READY and it asks to P_j
  - P_j in INITIAL: P_j abort
  - P_j in READY: nothing can be done
  - P_j in ABORT/COMMIT: P_j send "vote-commit"/"vote-abort to P_i

PARTICIPANTS

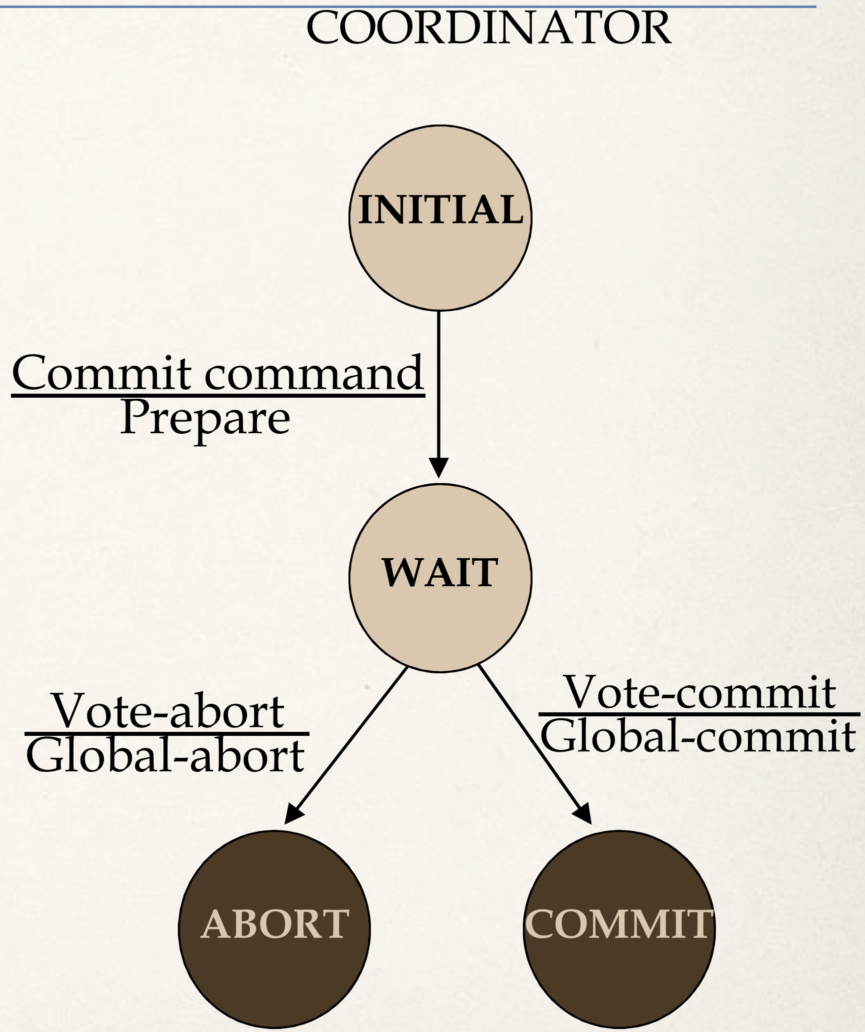


Re-election of the coordinator

- If participants can communicate …
- … and all of them know that the coordinator site is the only failing one
- then another coordinator is elected and the protocol is re-started
  - ➡ Election by ordering participants or by any voting procedure
- Does not work if a participant site fails besides the coordinator. Indeed:
  - ➡ Participant receive communication from coordinator
  - ➡ Participant terminate transaction accordingly
  - ➡ Participant and coordinator sites both fail
  - ➡ A new execution of the protocol among the remaining participants through re-election of coordinator might lead to a different decision
- 2PC is a blocking protocol

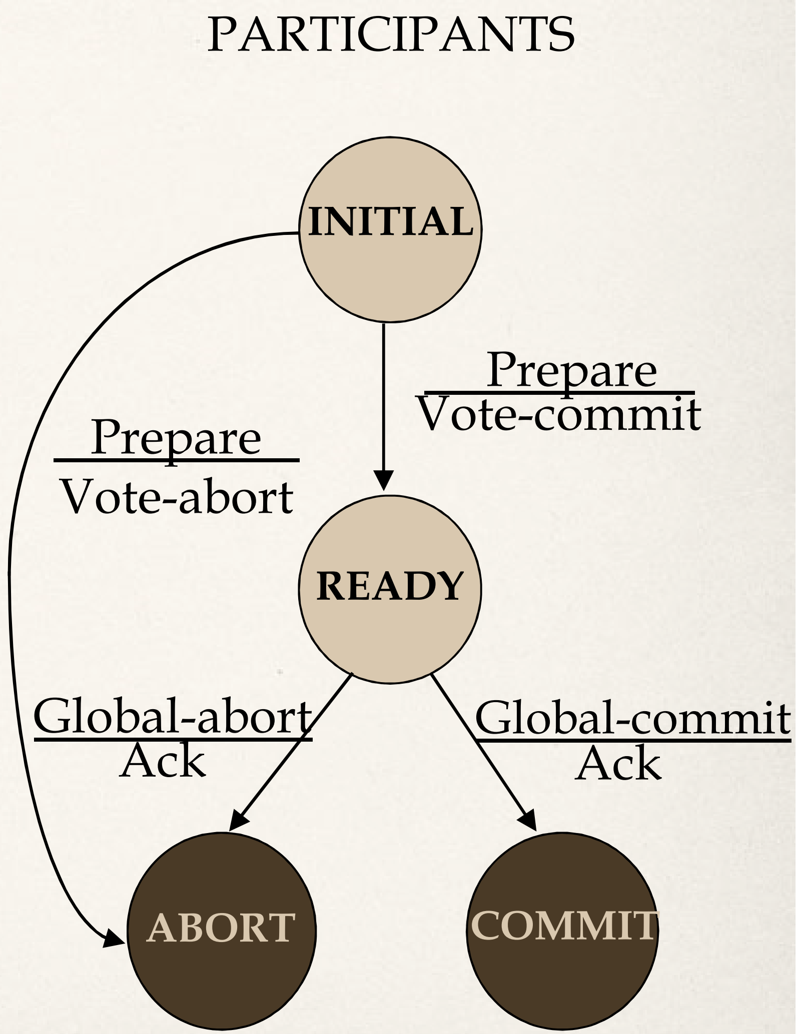
Site Failures - 2PC Recovery

- Failure in INITIAL
  - ➡ Start the commit process upon recovery
- Failure in WAIT
  - ➡ Restart the commit process upon recovery
- Failure in ABORT/COMMIT
  - ➡ Nothing special if all the acks have been received
  - ➡ Otherwise invoke the termination protocol for timeout in ABORT/COMMIT



Site Failures - 2PC Recovery

- Failure in INITIAL
  - ➡ Unilaterally abort upon recovery
- Failure in READY
  - ➡ The coordinator has been informed about the local decision
  - ➡ Treat as timeout in READY state and invoke the termination protocol
- Failure in ABORT or COMMIT
  - ➡ Nothing special needs to be done



2PC Recovery Protocols – Additional Cases

Arise due to non-atomicity of log and message send actions

- Coordinator site fails after writing "begin_commit" log and before sending "prepare" command
  - ➠ treat it as a failure in WAIT state; invoke recovery protocol from WAIT (send "prepare" command)
- Participant site fails after writing "ready" record in log but before "vote-commit" is sent
  - ➠ treat it as failure in READY state
  - ➠ invoke recovery protocol from READY
- Participant site fails after writing "abort" record in log but before "vote-abort" is sent
  - ➠ no need to do anything upon recovery

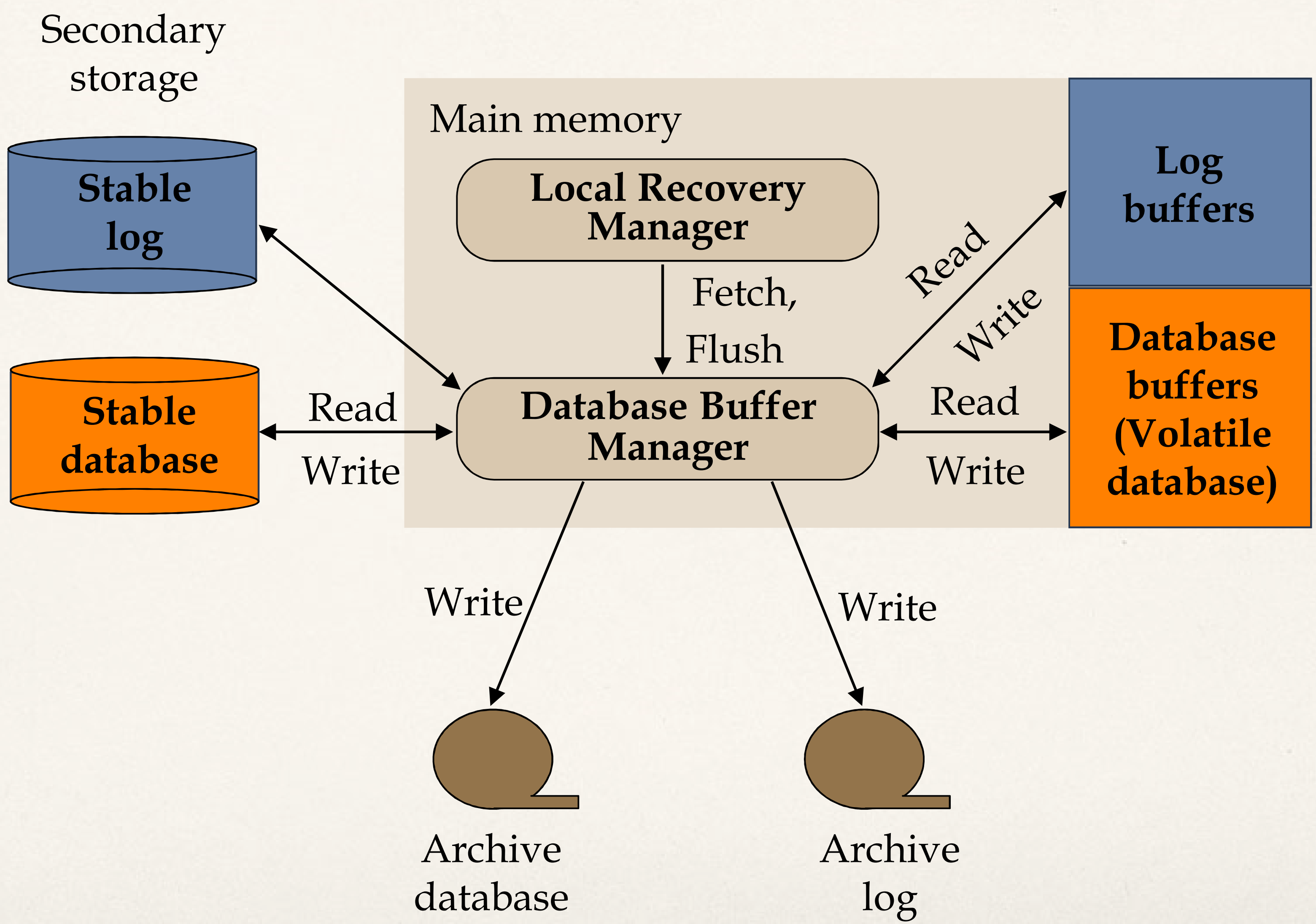
2PC Recovery Protocols – Additional Cases (cont'd)

- Coordinator site fails after logging its final decision record but before sending its decision to the participants
  - coordinator treats it as a failure in COMMIT or ABORT state
  - participants treat it as timeout in the READY state
- Participant site fails after writing "abort" or "commit" record in log but before acknowledgement is sent
  - participants treat it as failure in COMMIT or ABORT state
    - send ACK message upon request
  - coordinator will handle it by timeout in COMMIT or ABORT state

Problem With 2PC

- Blocking
  - "Ready" state implies that the participant waits for the coordinator
  - If coordinator fails, site is blocked until recovery
  - Blocking reduces availability
- Independent recovery is not possible
- However, it is known that:
  - Independent recovery protocols exist only for single site failures; no independent recovery protocol exists which is resilient to multiple-site failures.
- 3PC is non-blocking (for (single) site failures)
- Communication line failures (network partitioning) are more problematic
  - No non-blocking protocol exists

Media Failures – Full Architecture



More Problematic Failure Types

- We only considered *failures of omission*
  - ➡ A message is not received, a site is unresponsive
- *Failures of commissions*
  - ➡ Implementation errors (system does not work as expected): incorrect messages
  - ➡ Malicious behaviors: a participant pretends to be the coordinator
  - ➡ Addressed using *byzantine agreement*