Module 8
Fault Tolerance

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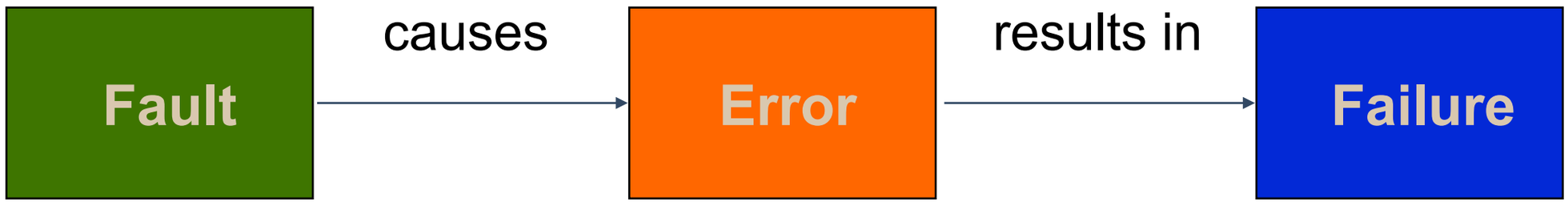
Dependability

- Reliability
  - A measure of success with which a system conforms to some authoritative specification of its behavior.
  - Probability that the system has not experienced any failures within a given time period.
  - Typically used to describe systems that cannot be repaired or where the continuous operation of the system is critical.
- Availability
  - The fraction of the time that a system meets its specification.
  - The probability that the system is operational at a given time *t*.
- Safety
  - When the system temporarily fails to conform to its specification, nothing catastrophic occurs.
- Maintainability
  - Measure of how easy it is to repair a system.

Fundamental Definitions

- Failure
  - ➡ The deviation of a system from the behavior that is described in its specification.
- Error
  - ➡ The part of the state which is incorrect.
- Fault
  - ➡ Cause of an error.

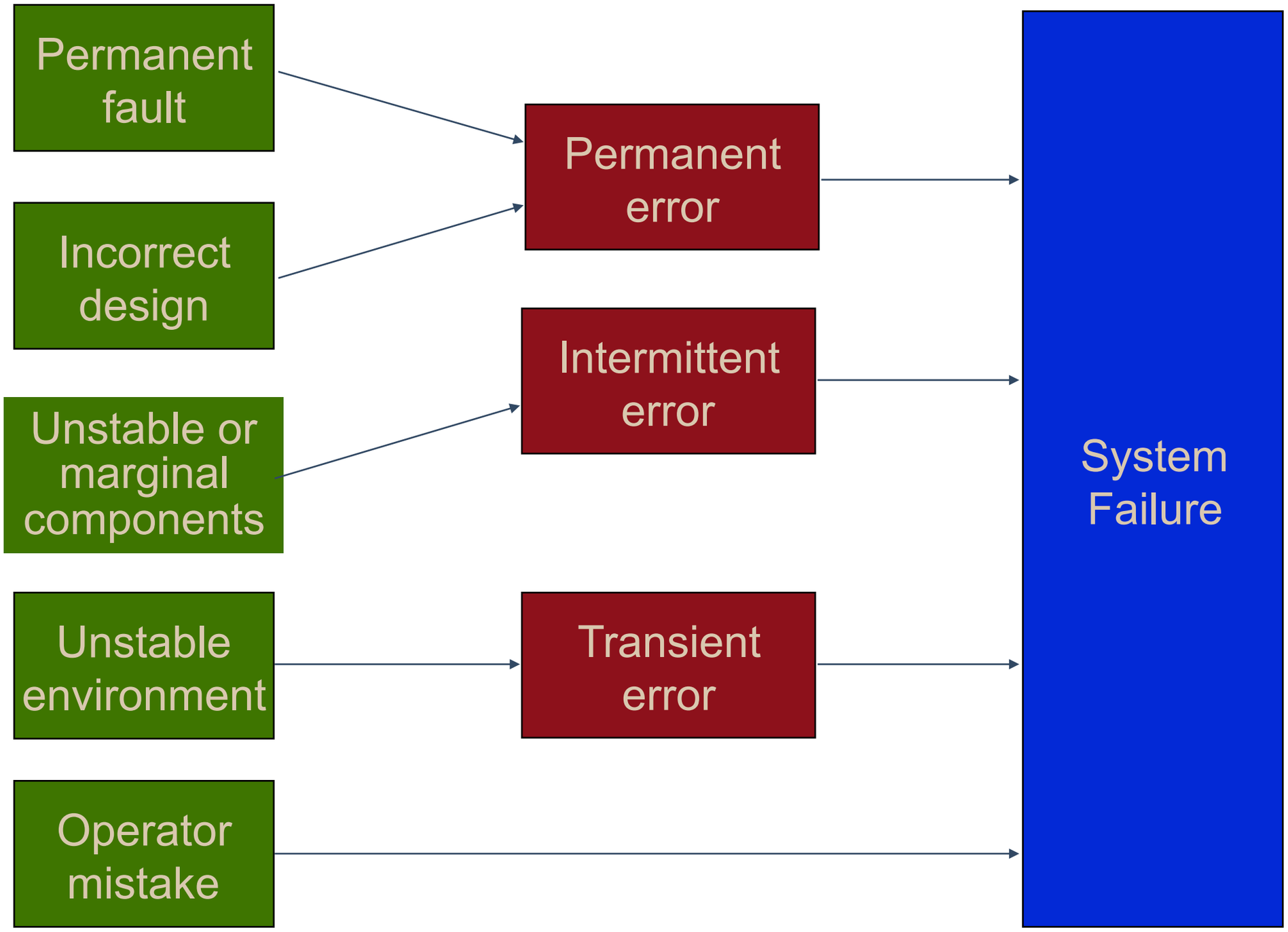
Faults to Failures



Types of Faults

- Hard faults
  - ➡ Permanent
  - ➡ Resulting failures are called hard failures
- Soft faults
  - ➡ Transient or intermittent
  - ➡ Resulting failures are called soft failures

Fault Classification



Failure Models

Type of failure	Description
Crash failure	A server halts, but is working correctly until it halts
Omission failure *Receive omission* *Send omission*	A server fails to respond to incoming requests A server fails to receive incoming messages A server fails to send messages
Timing failure	A server's response lies outside the specified time interval
Response failure *Value failure* *State transition failure*	The server's response is incorrect The value of the response is wrong The server deviates from the correct flow of control
Arbitrary failure	A server may produce arbitrary responses at arbitrary times

How to Improve Dependability

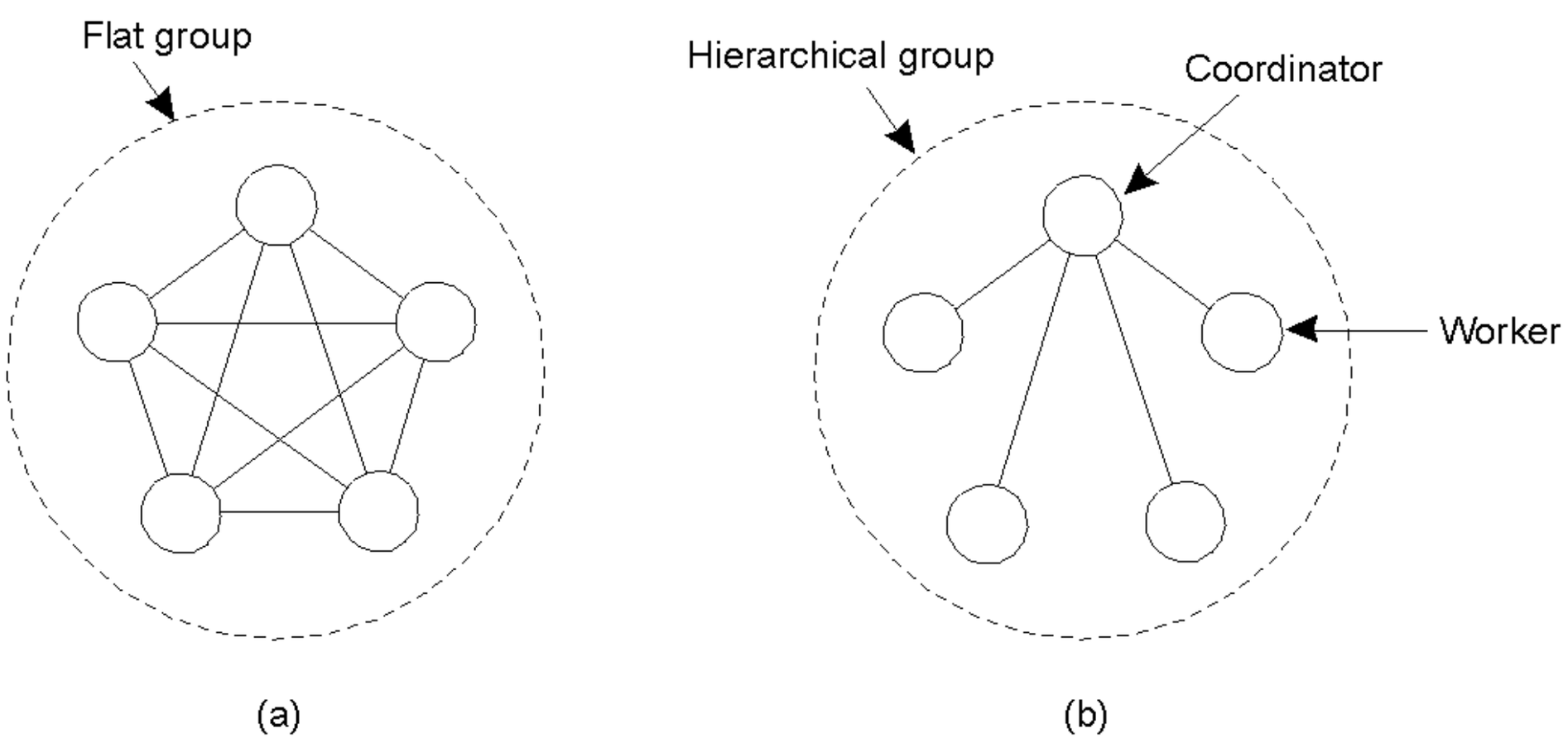
- Mask failures by redundancy
  - Information redundancy
    - E.g., add extra bits to detect and recovered data transmission errors
  - Time redundancy
    - Transactions; e.g., when a transaction aborts re-execute it without adverse effects.
  - Physical redundancy
    - Hardware redundancy
      - Take a distributed system with 4 file servers, each with a 0.95 chance of being up at any instant
      - The probability of all 4 being down simultaneously is $0.05^4 = 0.000006$
      - So the probability of at least one being available (i.e., the reliability of the full system) is 0.999994, far better than 0.95
      - If there are 2 servers, then the reliability of the system is $(1-0.05^2) = 0.9975$
    - Software redundancy
      - Process redundancy with similar considerations
- A design that does not require simultaneous functioning of a substantial number of critical components.

Hardware Redundancy

- Two computers are employed for a single application, one acting as a standby
  - ➡ Very costly, but often very effective solution
- Redundancy can be planned at a finer grain
  - ➡ Individual servers can be replicated
  - ➡ Redundant hardware can be used for non-critical activities when no faults are present
  - ➡ Redundant routes in network

Process Redundancy

- Process groups
  - ➡ All members of a group receive a message sent to the group.
  - ➡ If one process fails, others can take over.
  - ➡ Can be dynamic; processes can have multiple memberships.
  - ➡ Flat versus hierarchical groups:



From Tanenbaum and van Steen, Distributed Systems: Principles and Paradigms

Management of Replicated Processes

- Primary copy
  - ➡ Primary-backup setup
  - ➡ Coordinator is the primary that coordinates all updates
  - ➡ If coordinator fails, one backup takes over (usually through an election procedure)
  - ➡ Processes are organized hierarchically
- Replicated-writes
  - ➡ Active replication and quorum-based protocols
  - ➡ Flat group organization
  - ➡ No single points of failure

Fault Tolerance of Process Groups

- A system is *k fault tolerant* if it can survive faults in *k* components and still meets its specification.
- If failures are safe (silent), then *k*+1 processes are sufficient to get *k* fault tolerance.
- In case of arbitrary failures, 2*k*+1 processes are required (since *k* failing processes can all generate the same result by chance)
  - ➡ This assumes that each process reaches its decision independently
  - ➡ What if processes gang up to produce wrong results? General problem is having a process group reach an *agreement*.
    - ✦ In this case you need 2*k*+1 correctly functioning processes, for a total of 3*k*+1 processes.
- In both cases we assume that communication failures do not occur.

Communication Failures

- Point-to-point communication
  - ➡ TPC protocol masks the failures by acknowledgement and retransmission
- RPC and RMI semantics in the presence of failures
  - ➡ We studies these under the respective topics
    - ➡ See slides 3-13 to 3-19 for RPC
    - ➡ See slides 3-43 to 3-45 for RMI

Transactional Dependability

- Problem: How to maintain
  - ➡ atomicity
  - ➡ durability

  properties of transactions
- Focus is on data: Failures that affect ACID properties of data
  - ➡ Transaction failures
    - ✦ Transaction aborts (unilaterally or due to deadlock)
    - ✦ Avg. 3% of transactions abort abnormally
  - ➡ System (site) failures
    - ✦ Failure of processor, main memory, power supply, …
    - ✦ Main memory contents are lost, but secondary storage contents are safe
    - ✦ Partial vs. total failure
  - ➡ Media failures
    - ✦ Failure of secondary storage devices such that the stored data is lost
    - ✦ Head crash/controller failure
  - ➡ Communication failures
    - ✦ Lost/undeliverable messages
    - ✦ Network partitioning

Distributed Reliability Protocols

- Commit protocols
  - ➡ How to execute commit command for distributed transactions.
  - ➡ Issue: how to ensure atomicity and durability?
    - ✦ A transaction that executes at different sites has to complete (i.e., abort or commit) the same way everywhere
- Termination protocols
  - ➡ If a failure occurs, how can the remaining operational sites deal with it.
  - ➡ 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 do the sites where the failure occurred deal with it.
  - ➡ Independent : a failed site can determine the outcome of a transaction without having to obtain remote information.

Two-Phase Commit (2PC)

Phase 1: The coordinator gets the participants ready to commit their writes

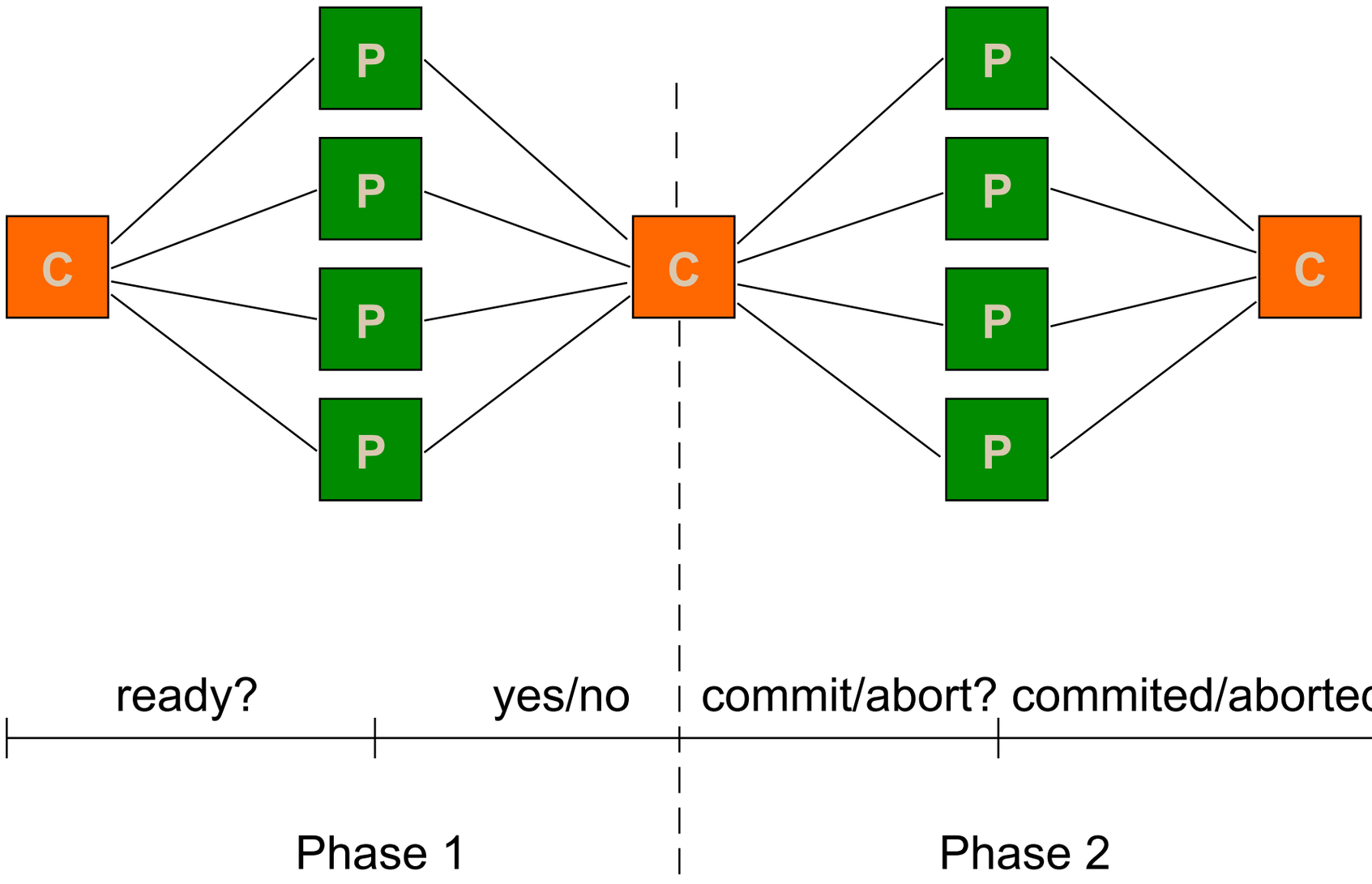
Phase 2: Everybody commits

- **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

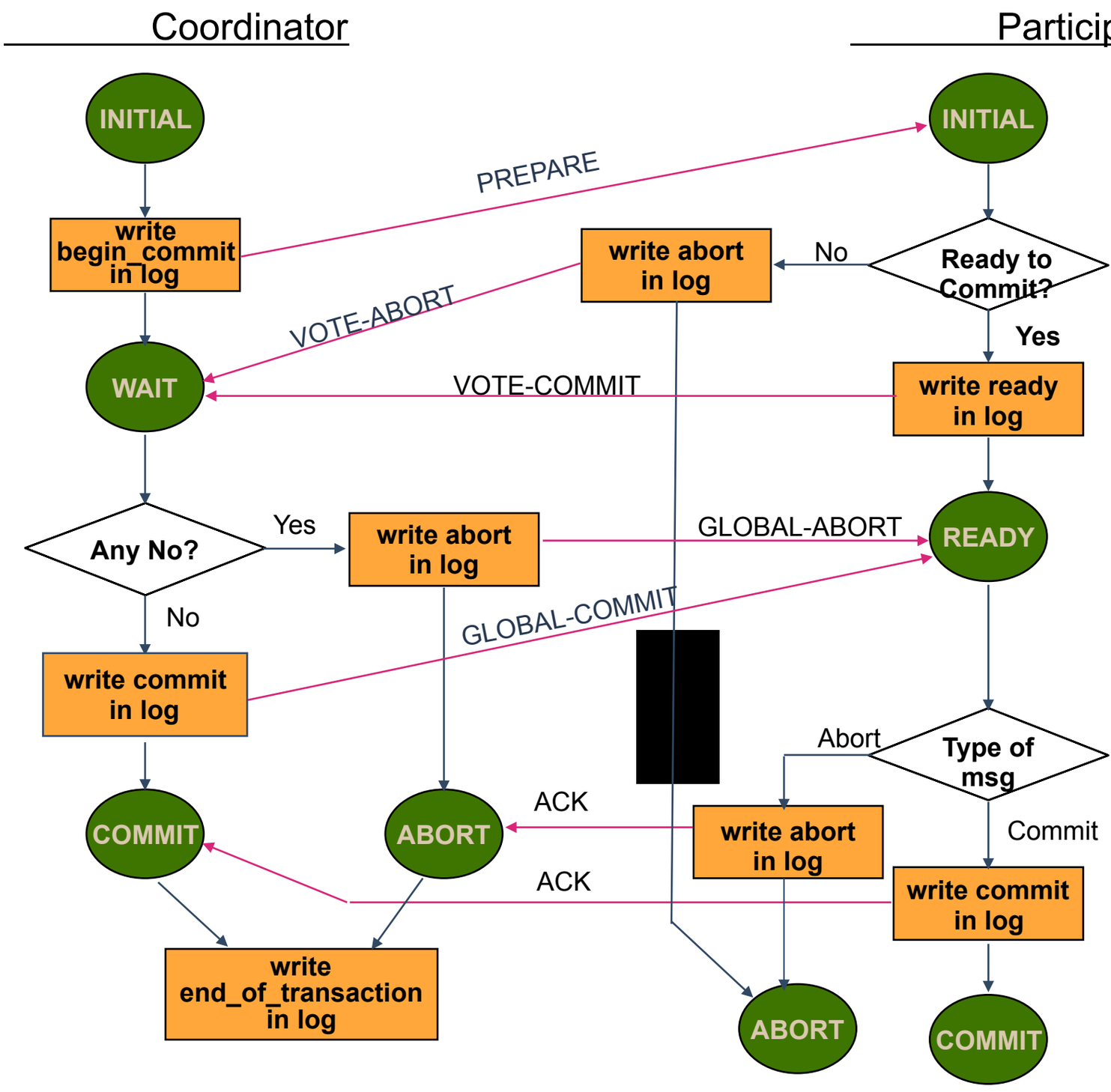
Global Commit Rule:

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

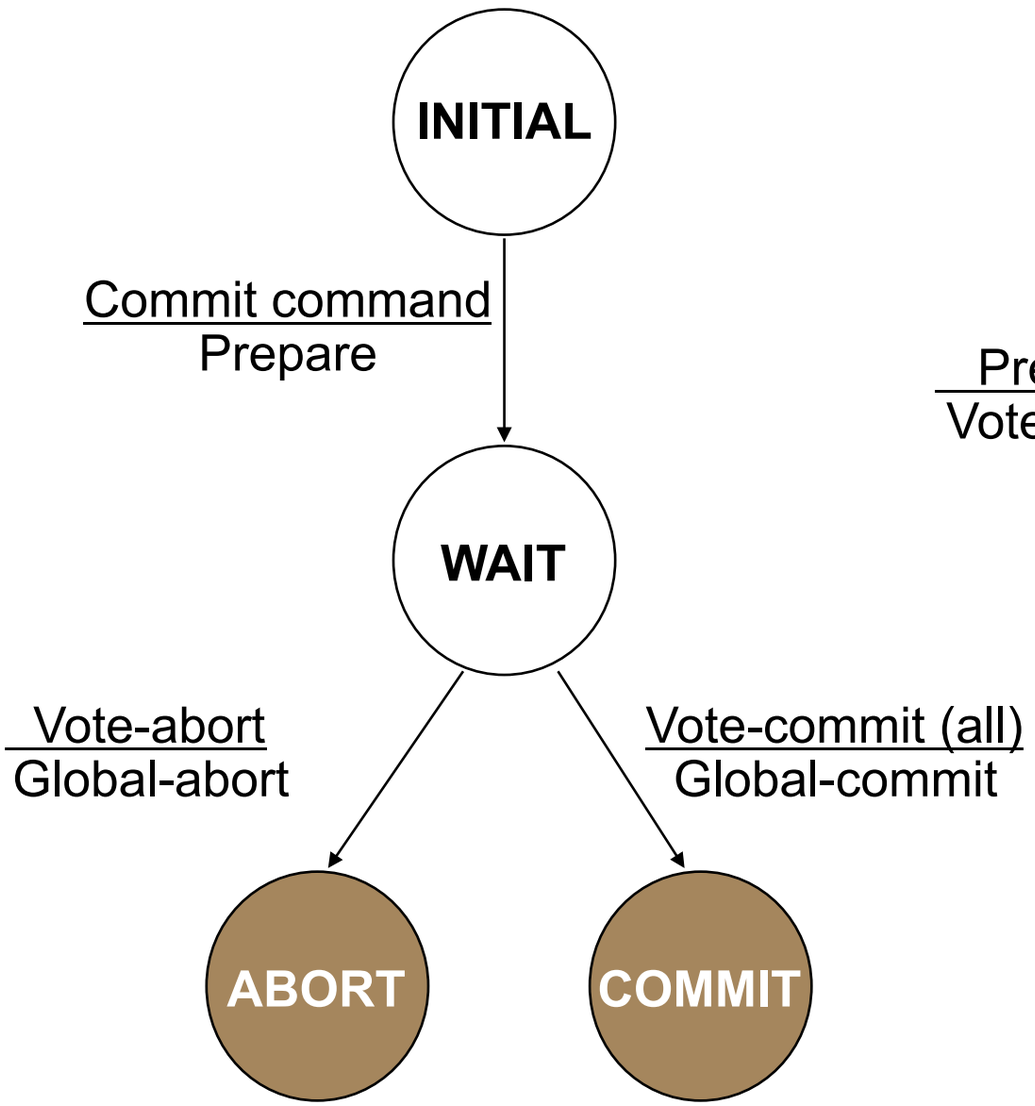
Centralized 2PC



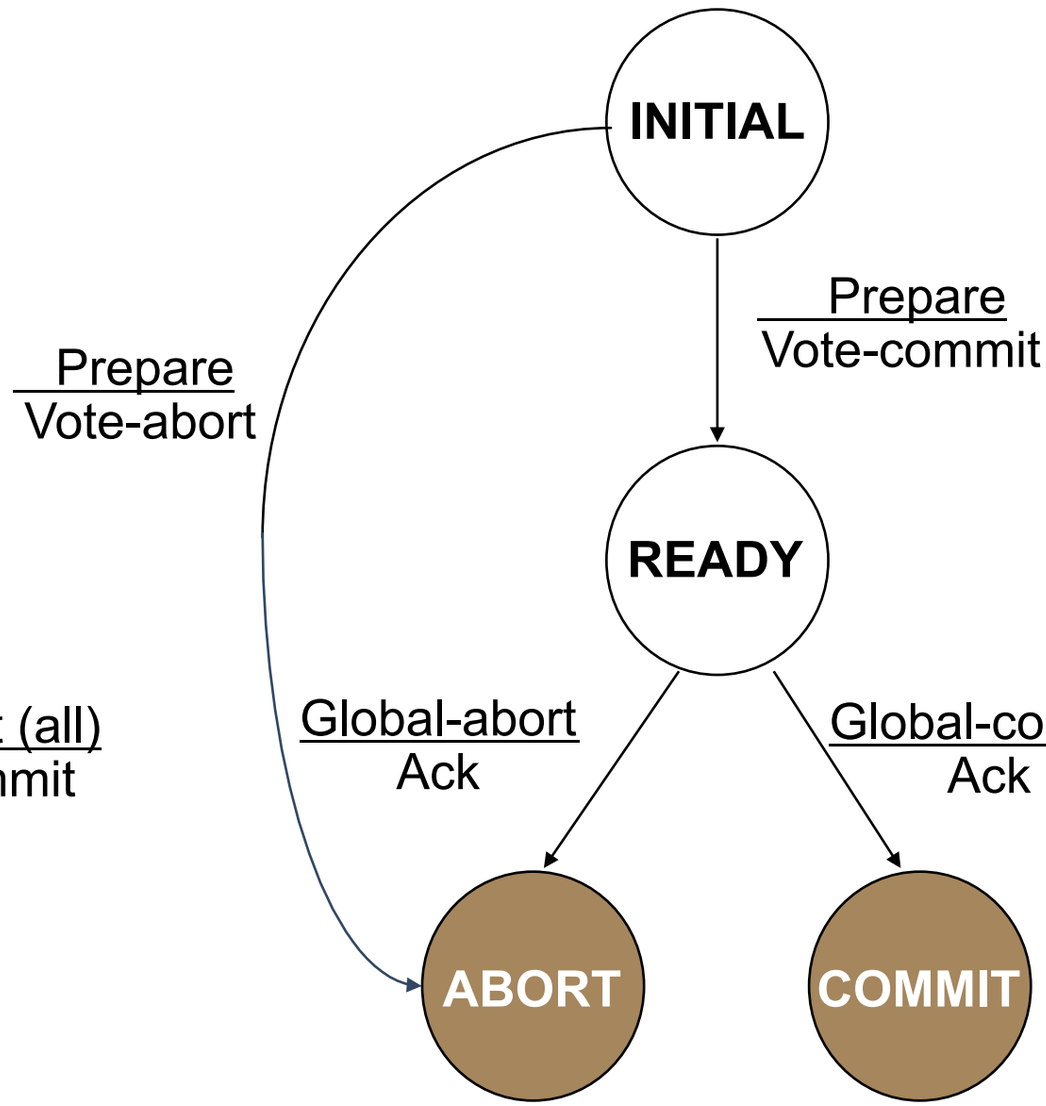
2PC Protocol Actions



State Transitions in 2PC



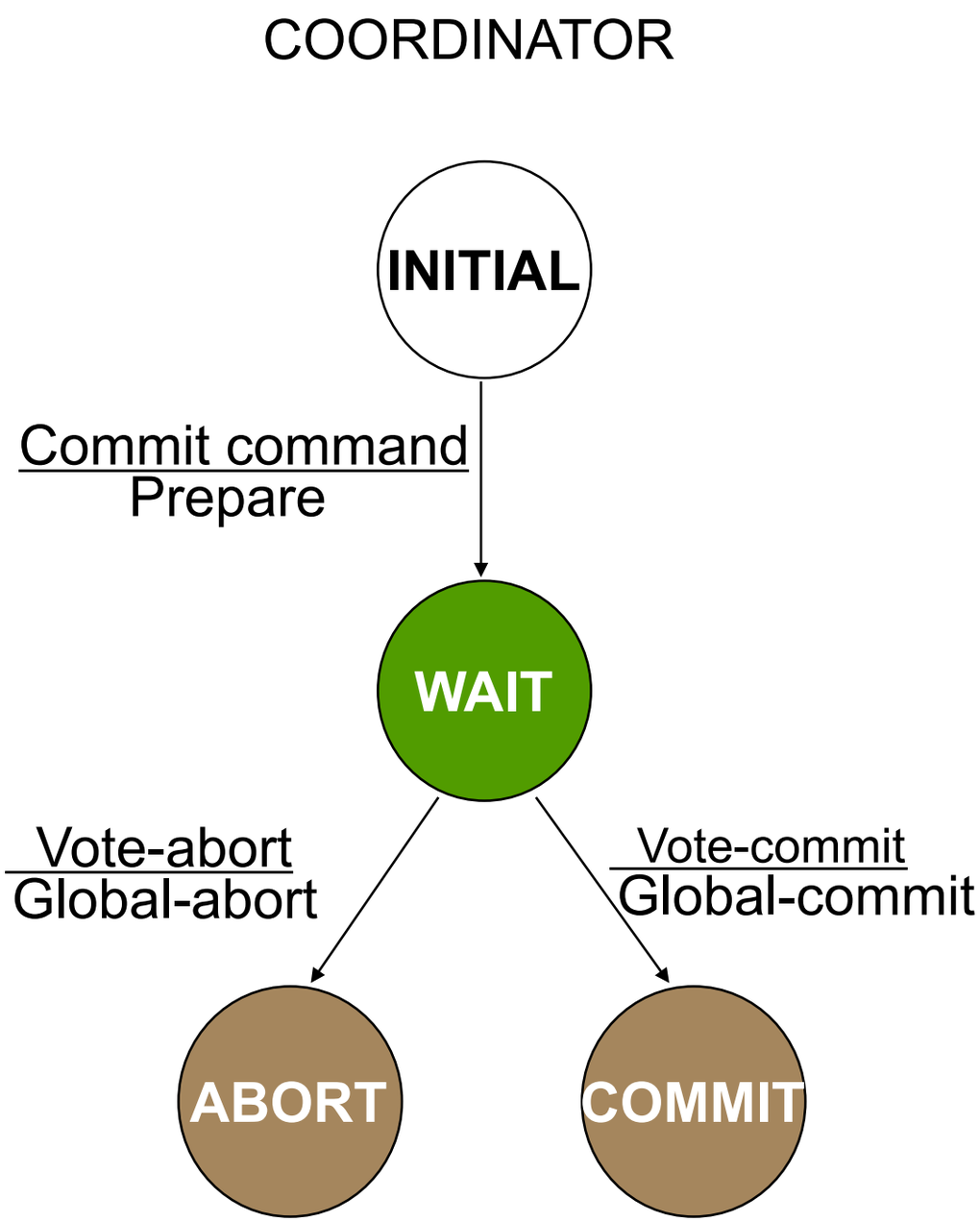
Coordinator



Participants

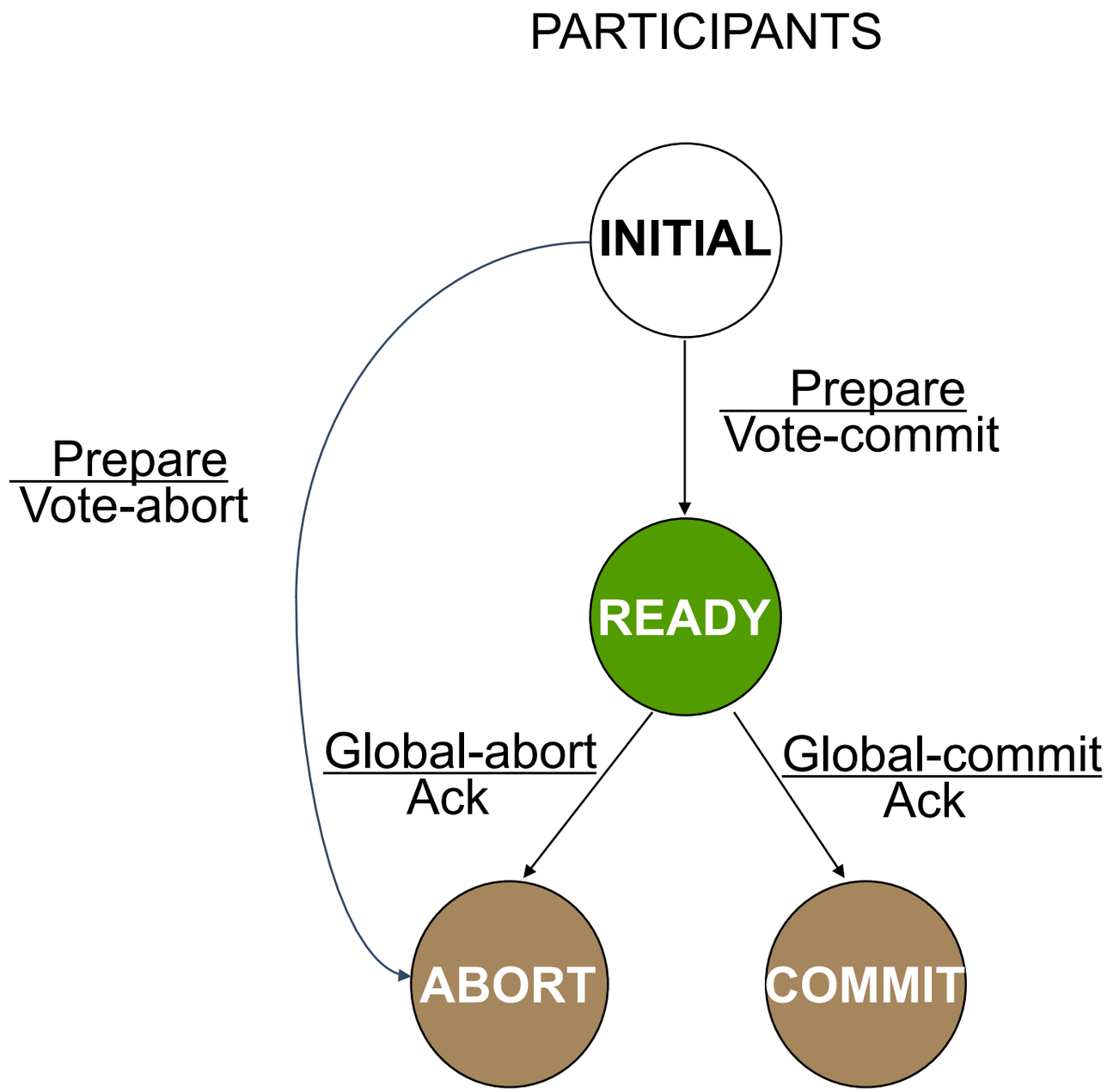
Site Failures - 2PC Termination

- Timeout in INITIAL
  - ➡ Who cares
- Timeout in WAIT
  - ➡ Cannot unilaterally commit
  - ➡ Can unilaterally abort
- Timeout in ABORT or COMMIT
  - ➡ Stay blocked and wait for the acks



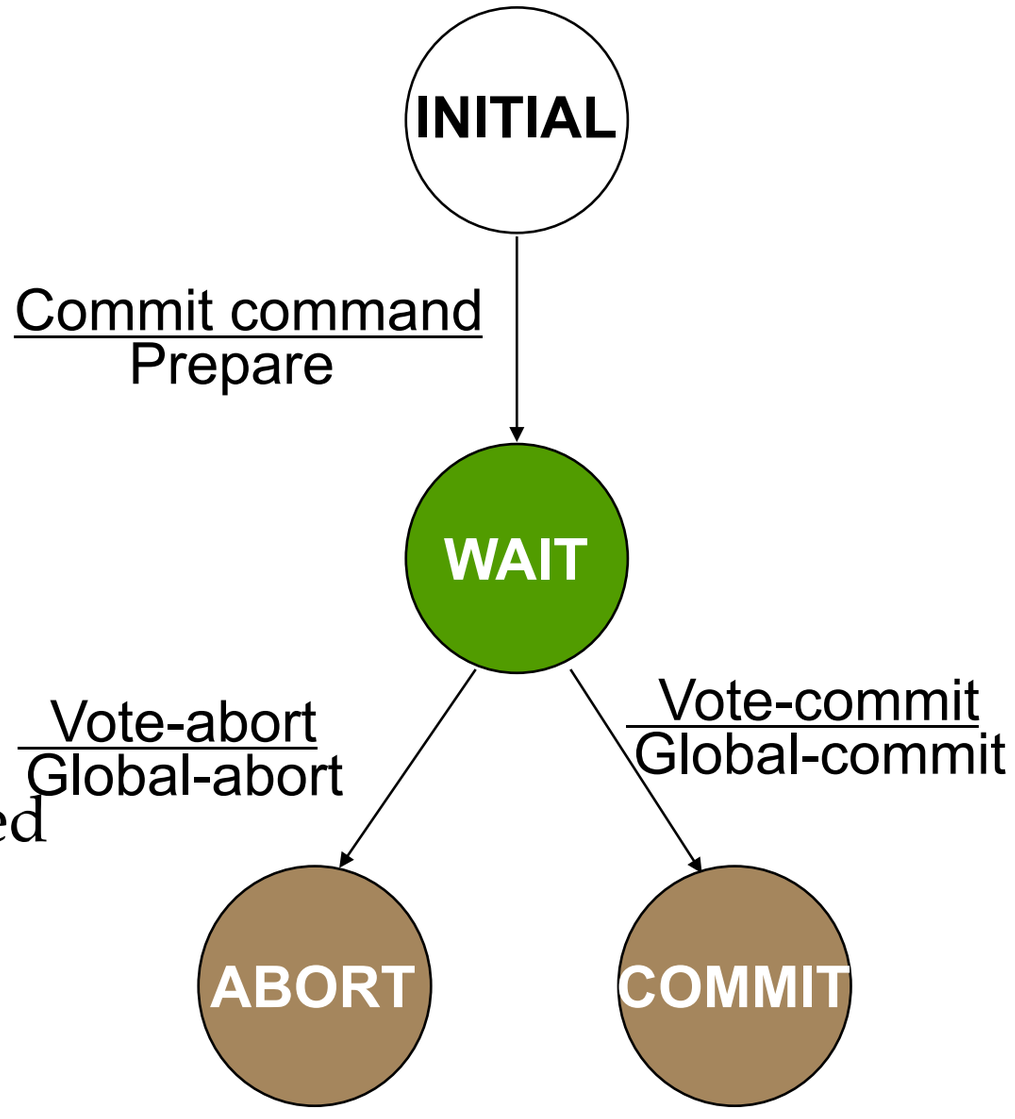
Site Failures - 2PC Termination

- Timeout in INITIAL
  - ➡ Coordinator must have failed in INITIAL state
  - ➡ Unilaterally abort
- Timeout in READY
  - ➡ Stay blocked



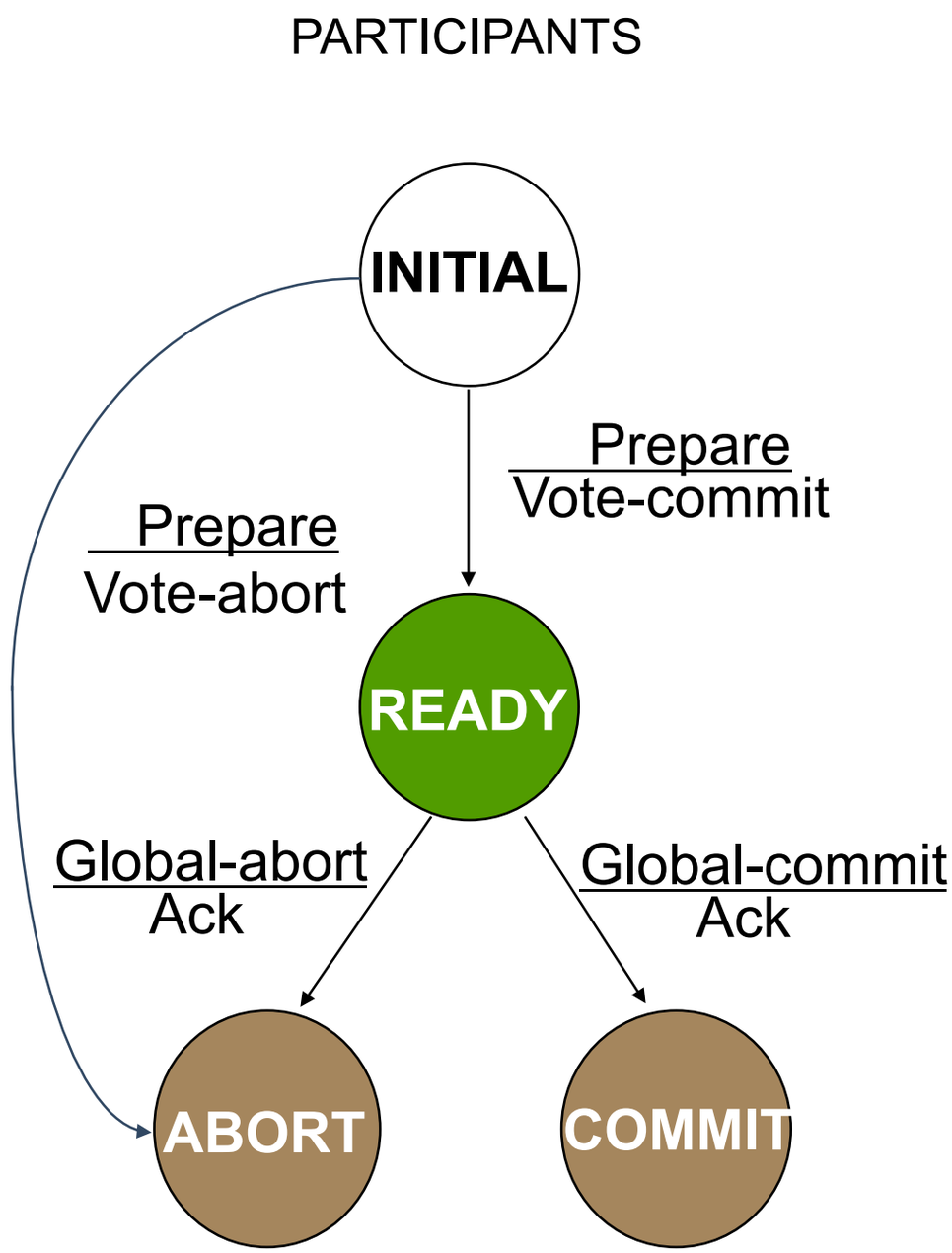
Site Failures - 2PC Recovery

- Failure in INITIAL
  - ➡ Start the commit process upon recovery
- Failure in WAIT
  - ➡ Restart the commit process upon recovery
- Failure in ABORT or COMMIT
  - ➡ Nothing special if all the acks have been received
  - ➡ Otherwise the termination protocol is involved



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; 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
  - ➡ alternatively, can send "vote-commit" upon recovery
- 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 Case

- 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
  - ➡ participant treats it as failure in COMMIT or ABORT state
  - ➡ coordinator will handle it by timeout in COMMIT or ABORT state

Problem With 2PC

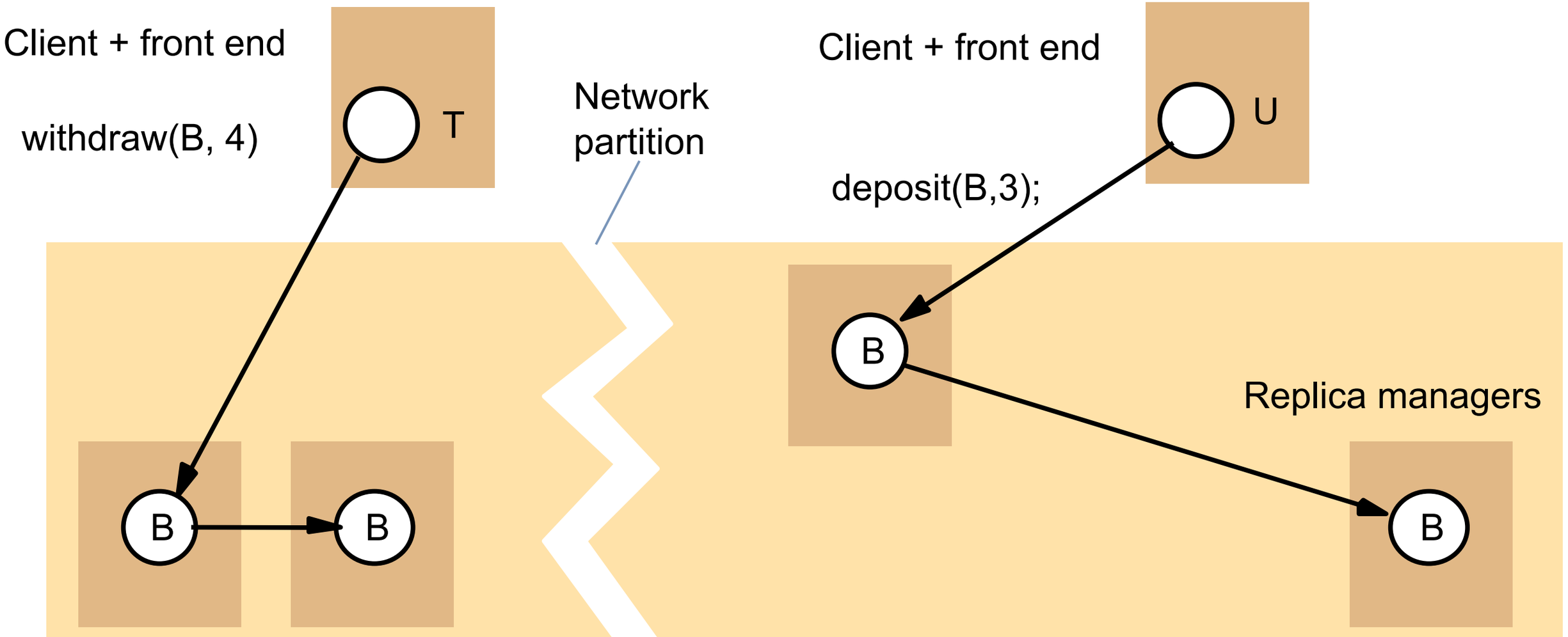
- Blocking
  - Ready implies that the participant waits for the coordinator
  - If coordinator fails, site is blocked until recovery
  - Blocking reduces availability
- Independent recovery is not possible
- However, it is known that:
  - Independent recovery protocols exist only for single site failures; no independent recovery protocol exists which is resilient to multiple-site failures.
- So we search for these protocols – 3PC

Quorum Protocols for Network Partitioning

- The network partitioning problem is handled by the commit protocol.
- Every site is assigned a vote V_i.
- Total number of votes in the system V
- Abort quorum V_a, commit quorum V_c
  - ➡ $V_a + V_c > V$ where $0 \leq V_a, V_c \leq V$
  - ➡ Before a transaction commits, it must obtain a commit quorum V_c
  - ➡ Before a transaction aborts, it must obtain an abort quorum V_a

Network Partitioning & Replication

- A group of replica managers are partitioned into two or more subgroups such that members of one subgroup can communicate with each other but members of different subgroups cannot communicate with one another.



Replica Management with Network Partitioning

- Optimistic approach
  - ➡ Available copies with validation
    - ✦ Let each partition perform updates freely
    - ✦ Validate when partition is repaired and those that violate one-copy serializability are aborted.
- Pessimistic
  - ➡ Quorum-based
    - ✦ Reduce availability (even when there is no partitioning)
    - ✦ Updates can only occur in the partition that has a majority of the replica managers