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# Principles of Distributed Database Systems

# Outline

- Introduction
- Distributed and parallel database design
- Distributed data control
- Distributed Transaction Processing
- Data Replication
- Database Integration – Multidatabase Systems
- Parallel Database Systems
- Peer-to-Peer Data Management
- Big Data Processing
- NoSQL, NewSQL and Polystores
- Web Data Management

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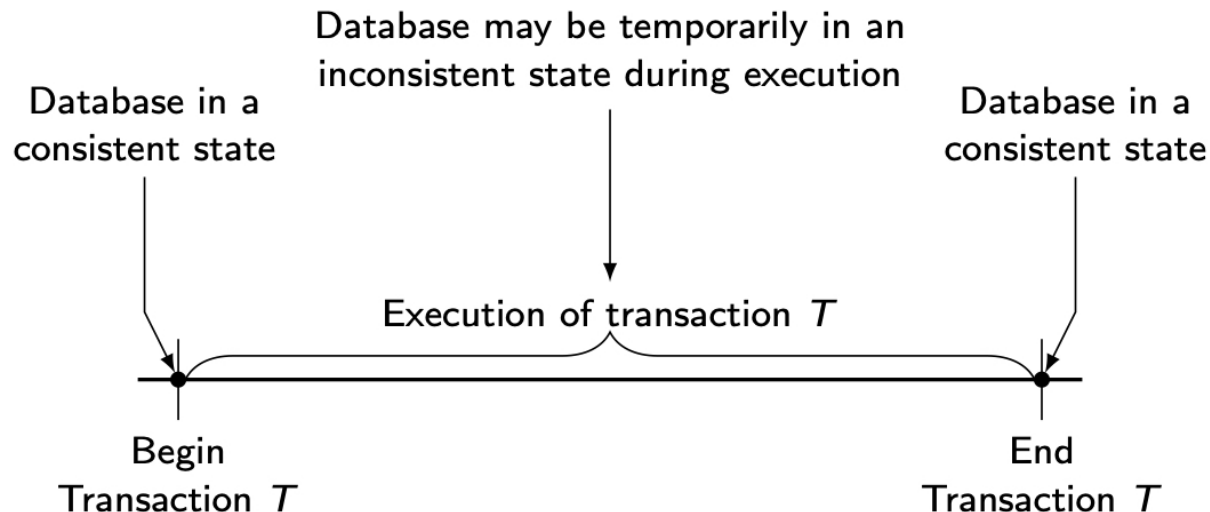
# Outline

- Distributed Transaction Processing
  - ▣ Distributed Concurrency Control
  - ▣ Distributed Reliability

# Transaction

A transaction is a collection of actions that make consistent transformations of system states while preserving system consistency.

- ❑ concurrency transparency
- ❑ failure transparency



# Transaction Characterization

**Begin\_transaction**

...

**Read**

**Read**

...

**Write**

**Read**

...

**Commit**

- **Read set (RS)**
  - The set of data items that are read by a transaction
- **Write set (WS)**
  - The set of data items whose values are changed by this transaction
- **Base set (BS)**
  - $RS \cup WS$

# Principles of Transactions

## **A**TCOMICITY

- ❑ all or nothing

## **C**ONSISTENCY

- ❑ no violation of integrity constraints

## **I**SOLATION

- ❑ concurrent changes invisible  $\Rightarrow$  serializable

## **D**URABILITY

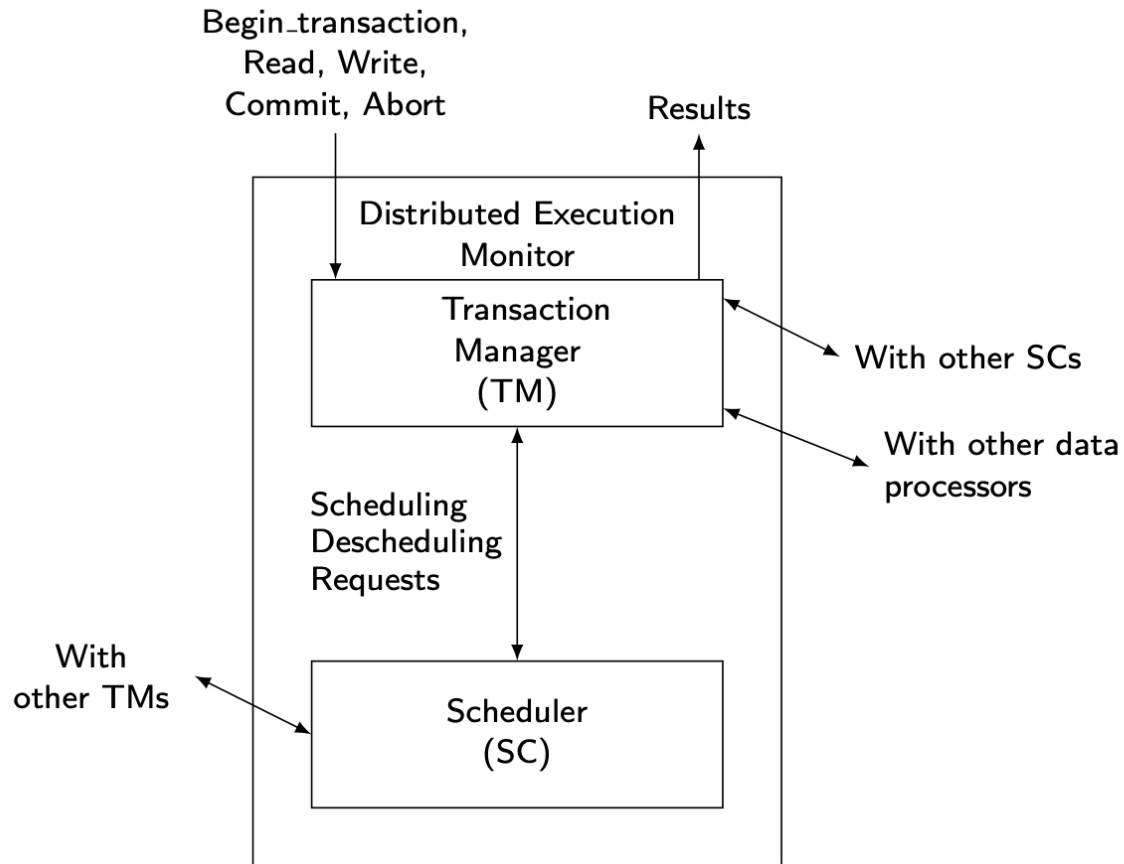
- ❑ committed updates persist

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# Transactions Provide...

- *Atomic* and *reliable* execution in the presence of failures
- *Correct* execution in the presence of multiple user accesses
- Correct management of *replicas* (if they support it)

# Distributed TM Architecture





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# Outline

- Distributed Transaction Processing
  - ▣ Distributed Concurrency Control
  - ▣ Distributed Reliability

# Concurrency Control

- The problem of synchronizing concurrent transactions such that the consistency of the database is maintained while, at the same time, maximum degree of concurrency is achieved.
- Enforce **isolation** property
- Anomalies:
  - Lost updates
    - The effects of some transactions are not reflected on the database.
  - Inconsistent retrievals
    - A transaction, if it reads the same data item more than once, should always read the same value.

# Serializability in Distributed DBMS

- Two histories have to be considered:
  - local histories
  - global history
- For global transactions (i.e., global history) to be **serializable**, two conditions are necessary:
  - Each local history should be serializable → **local serializability**
  - Two conflicting operations should be in the same relative order in all of the local histories where they appear together → **global serializability**

# Global Non-serializability

$T_1$ :    Read(x)  
           $x \leftarrow x - 100$   
          Write(x)  
          Read(y)  
           $y \leftarrow y + 100$   
          Write(y)  
          Commit

$T_2$ :    Read(x)  
          Read(y)  
          Commit

- $x$  stored at Site 1,  $y$  stored at Site 2
- $LH_1$ ,  $LH_2$  are individually serializable (in fact serial), but the two transactions are not globally serializable.

$LH_1 = \{R_1(x), W_1(x), R_2(x)\}$

$LH_2 = \{R_2(y), R_1(y), W_1(y)\}$

# Concurrency Control Algorithms

## ■ Pessimistic

- ❑ Two-Phase Locking-based (2PL)
  - Centralized (primary site) 2PL
  - Primary copy 2PL
  - Distributed 2PL
- ❑ Timestamp Ordering (TO)
  - Basic TO
  - Multiversion TO
  - Conservative TO

## ■ Optimistic

- ❑ Locking-based
- ❑ Timestamp ordering-based

# Locking-Based Algorithms

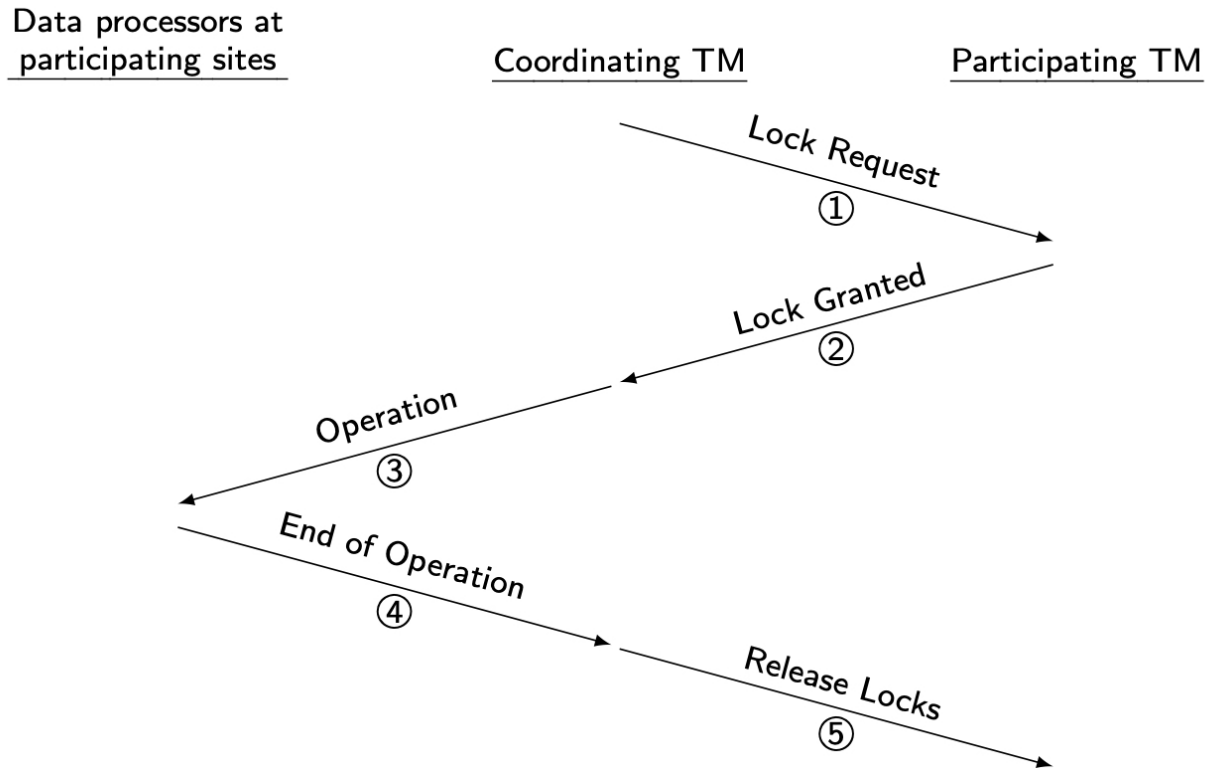
- Transactions indicate their intentions by requesting locks from the scheduler (called **lock manager**).
- Locks are either **read lock** (*rl*) [also called **shared lock**] or **write lock** (*wl*) [also called **exclusive lock**]
- Read locks and write locks conflict (because Read and Write operations are incompatible)

	<i>rl</i>	<i>wl</i>
<i>rl</i>	yes	no
<i>wl</i>	no	no

- Locking works nicely to allow concurrent processing of transactions.

# Centralized 2PL

- There is only one 2PL scheduler in the distributed system.
- Lock requests are issued to the central scheduler.

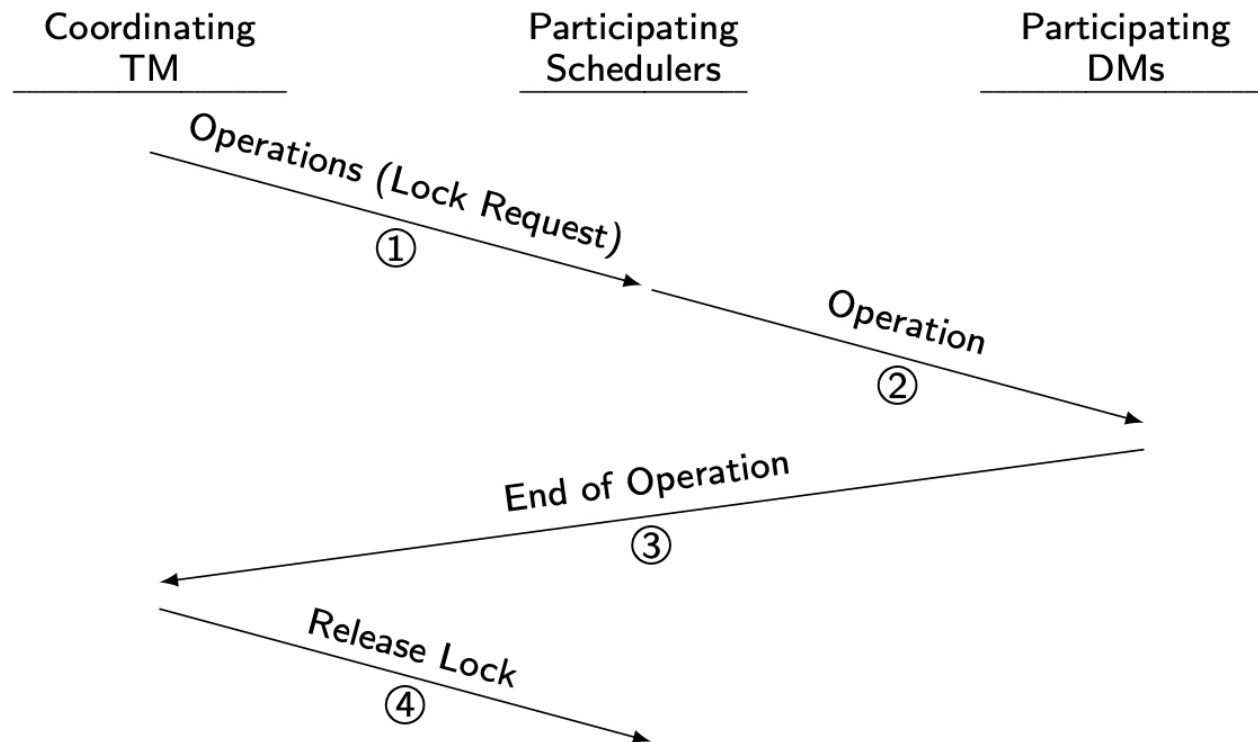


# Distributed 2PL

- 2PL schedulers are placed at each site. Each scheduler handles lock requests for data at that site.
- A transaction may read any of the replicated copies of item  $x$ , by obtaining a read lock on one of the copies of  $x$ . Writing into  $x$  requires obtaining write locks for all copies of  $x$ .

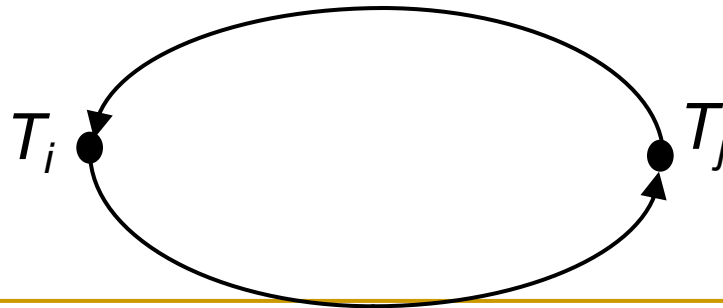


# Distributed 2PL Execution



# Deadlock

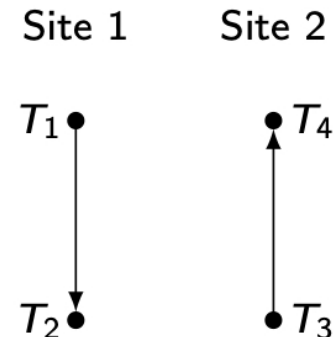
- A transaction is deadlocked if it is blocked and will remain blocked until there is intervention.
- Locking-based CC algorithms may cause deadlocks.
- TO-based algorithms that involve waiting may cause deadlocks.
- Wait-for graph
  - If transaction  $T_i$  waits for another transaction  $T_j$  to release a lock on an entity, then  $T_i \rightarrow T_j$  in WFG.



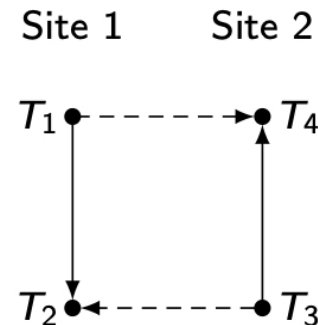
# Local versus Global WFG

- $T_1$  and  $T_2$  run at site 1,  $T_3$  and  $T_4$  run at site 2.
- $T_3$  waits for a lock held by  $T_4$  which waits for a lock held by  $T_1$  which waits for a lock held by  $T_2$  which, in turn, waits for a lock held by  $T_3$ .

Local WFG



Global WFG



# Deadlock Detection

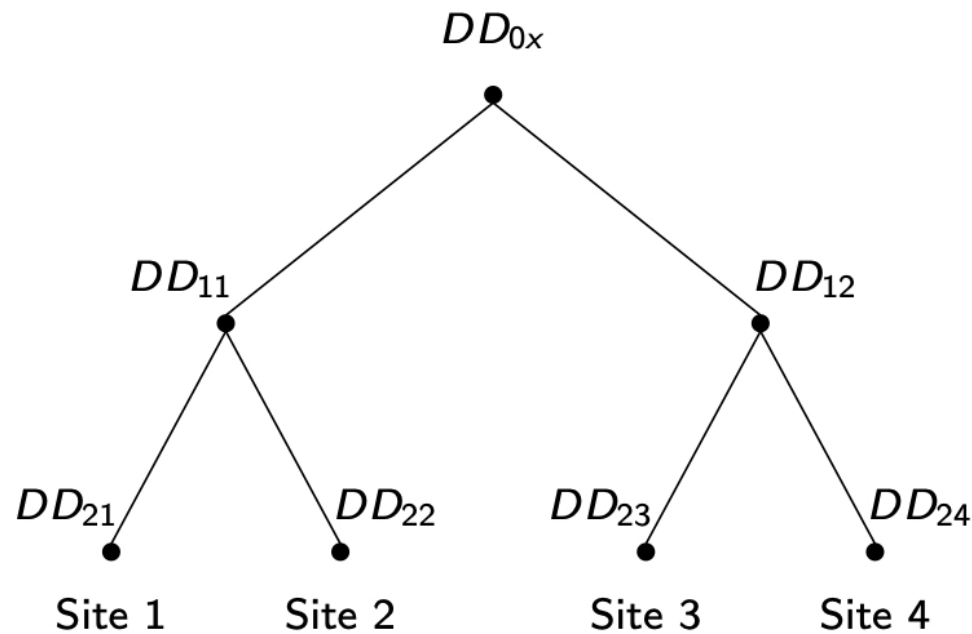
- Transactions are allowed to wait freely.
- Wait-for graphs and cycles.
- Topologies for deadlock detection algorithms
  - Centralized
  - Distributed
  - Hierarchical

# Centralized Deadlock Detection

- One site is designated as the deadlock detector for the system. Each scheduler periodically sends its local WFG to the central site which merges them to a global WFG to determine cycles.
- How often to transmit?
  - Too often  $\Rightarrow$  higher communication cost but lower delays due to undetected deadlocks
  - Too late  $\Rightarrow$  higher delays due to deadlocks, but lower communication cost
- Would be a reasonable choice if the concurrency control algorithm is also centralized.
- Proposed for Distributed INGRES

# Hierarchical Deadlock Detection

Build a hierarchy of detectors



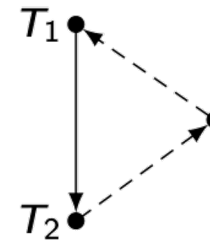
# Distributed Deadlock Detection

- Sites cooperate in detection of deadlocks.
- One example:

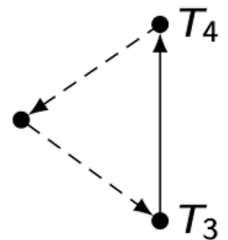
- Form local WFGs at each modified as follows:

- 1) Potential deadlock cycles from other sites are added as edges
- 2) Join these with regular edges
- 3) Pass these local WFGs to other sites

Site 1



Site 2



- Each local deadlock detector:

- looks for a cycle that does not involve the external edge. If it exists, there is a local deadlock which can be handled locally.
- looks for a cycle involving the external edge. If it exists, it indicates a **potential** global deadlock. Pass on the information to the next site.

# Timestamp Ordering

- 1 Transaction ( $T_i$ ) is assigned a globally unique timestamp  $ts(T_i)$ .
- 2 Transaction manager attaches the timestamp to all operations issued by the transaction.
- 3 Each data item is assigned a write timestamp ( $wts$ ) and a read timestamp ( $rts$ ):
  - ▢  $rts(x)$  = largest timestamp of any read on  $x$
  - ▢  $wts(x)$  = largest timestamp of any read on  $x$
- 4 Conflicting operations are resolved by timestamp order.

Basic T/O:

for  $R_i(x)$

**if**  $ts(T_i) < wts(x)$   
**then** reject  $R_i(x)$   
**else** accept  $R_i(x)$   
 $rts(x) \leftarrow ts(T_i)$

for  $W_i(x)$

**if**  $ts(T_i) < rts(x)$  **or**  $ts(T_i) < wts(x)$   
**then** reject  $W_i(x)$   
**else** accept  $W_i(x)$   
 $wts(x) \leftarrow ts(T_i)$



# Basic Timestamp Ordering

Two conflicting operations  $O_{ij}$  of  $T_i$  and  $O_{kl}$  of  $T_k \rightarrow O_{ij}$  executed before  $O_{kl}$  iff  $ts(T_i) < ts(T_k)$ .

- ❑  $T_i$  is called **older** transaction
- ❑  $T_k$  is called **younger** transaction

for  $R_i(x)$

**if**  $ts(T_i) < wts(x)$   
    **then** reject  $R_i(x)$   
    **else** accept  $R_i(x)$   
 $rts(x) \leftarrow ts(T_i)$

for  $W_i(x)$

**if**  $ts(T_i) < rts(x)$  **or**  $ts(T_i) < wts(x)$   
    **then** reject  $W_i(x)$   
    **else** accept  $W_i(x)$   
 $wts(x) \leftarrow ts(T_i)$

# Conservative Timestamp Ordering

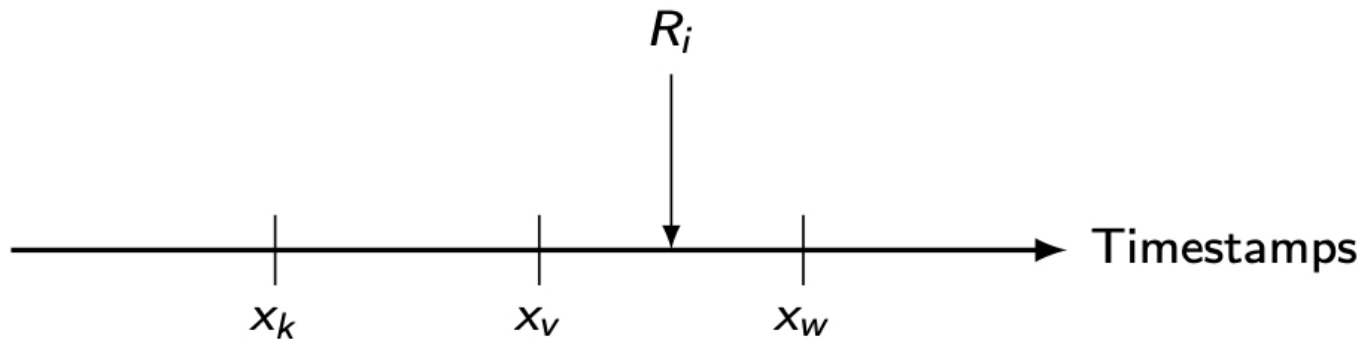
- Basic timestamp ordering tries to execute an operation as soon as it receives it
  - progressive
  - too many restarts since there is no delaying
- Conservative timestamping delays each operation until there is an assurance that it will not be restarted
- Assurance?
  - No other operation with a smaller timestamp can arrive at the scheduler
  - Note that the delay may result in the formation of deadlocks

# Multiversion Concurrency Control (MVCC)

- Do not modify the values in the database, create new values.
- Typically timestamp-based implementation
$$ts(T_i) < ts(x_r) < ts(T_j)$$
- Implemented in a number of systems: IBM DB2, Oracle, SQL Server, SAP HANA, BerkeleyDB, PostgreSQL

# MVCC Reads

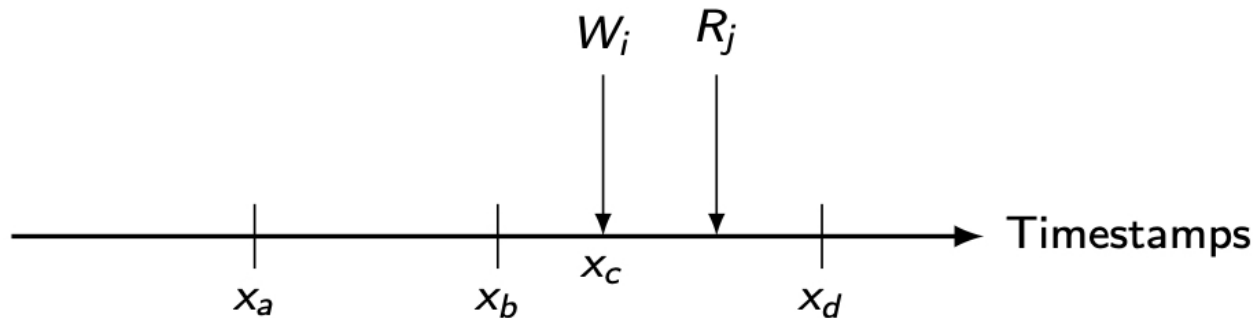
- A  $R_i(x)$  is translated into a read on one version of  $x$ .
  - Find a version of  $x$  (say  $x_v$ ) such that  $ts(x_v)$  is the largest timestamp less than  $ts(T_i)$ .



# MVCC Writes

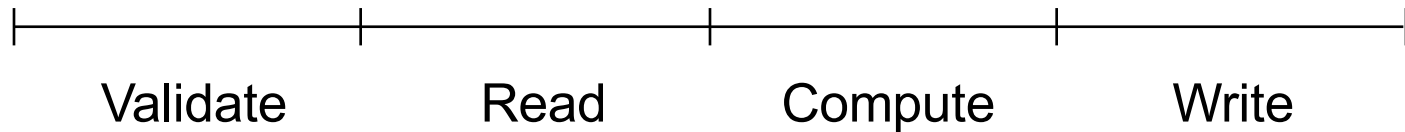
- A  $W_i(x)$  is translated into  $W_i(x_w)$  and accepted if the scheduler has not yet processed any  $R_j(x_r)$  such that

$$ts(T_i) < ts(x_r) < ts(T_j)$$

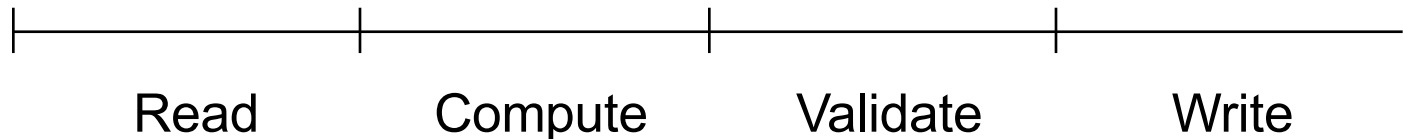


# Optimistic Concurrency Control Algorithms

Pessimistic execution



Optimistic execution

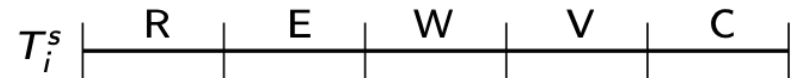
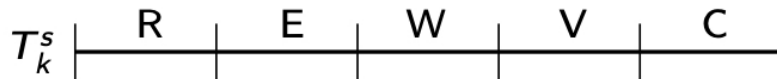


# Optimistic Concurrency Control Algorithms

- Transaction execution model: divide into subtransactions each of which execute at a site
  - $T_{ij}$ : transaction  $T_i$  that executes at site  $j$
- Transactions run independently at each site until they reach the end of their read phases
- All subtransactions are assigned a timestamp at the end of their read phase
- **Validation test** performed during validation phase. If one fails, all rejected.

# Optimistic CC Validation Test

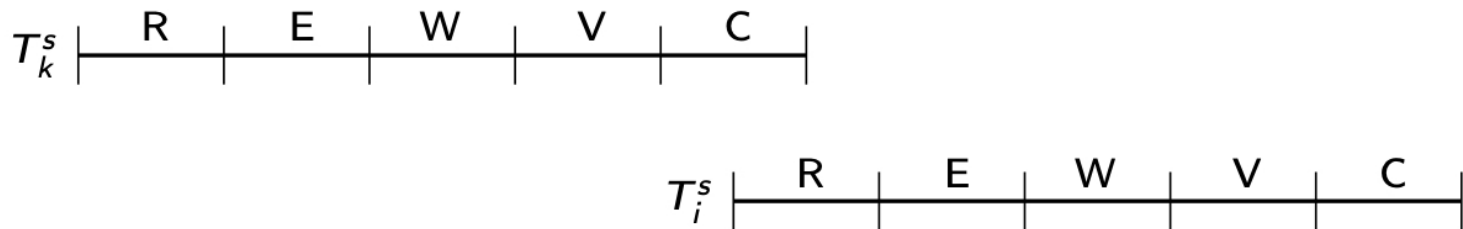
- 1 If all transactions  $T_k$  where  $ts(T_k) < ts(T_{ij})$  have completed their write phase before  $T_{ij}$  has started its read phase, then validation succeeds
  - Transaction executions in serial order





# Optimistic CC Validation Test

- ② If there is any transaction  $T_k$  such that  $ts(T_k) < ts(T_{ij})$  and which completes its write phase while  $T_{ij}$  is in its read phase, then validation succeeds if  $WS(T_k) \cap RS(T_{ij}) = \emptyset$
- Read and write phases overlap, but  $T_{ij}$  does not read data items written by  $T_k$

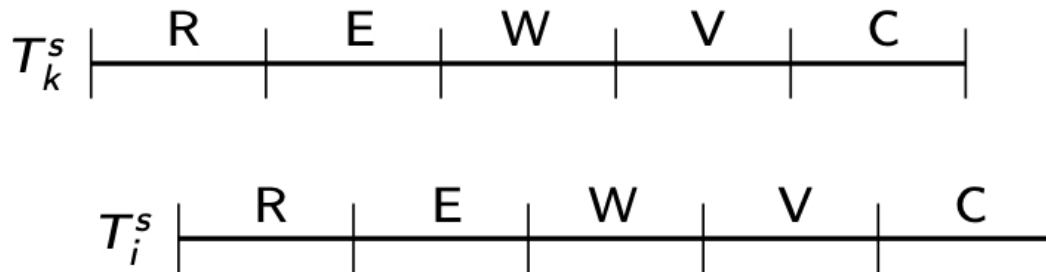


# Optimistic CC Validation Test

- ③ If there is any transaction  $T_k$  such that  $ts(T_k) < ts(T_{ij})$  and which completes its read phase before  $T_{ij}$  completes its read phase, then validation succeeds if

$$WS(T_k) \cap RS(T_{ij}) = \emptyset \text{ and } WS(T_k) \cap WS(T_{ij}) = \emptyset$$

- They overlap, but don't access any common data items.



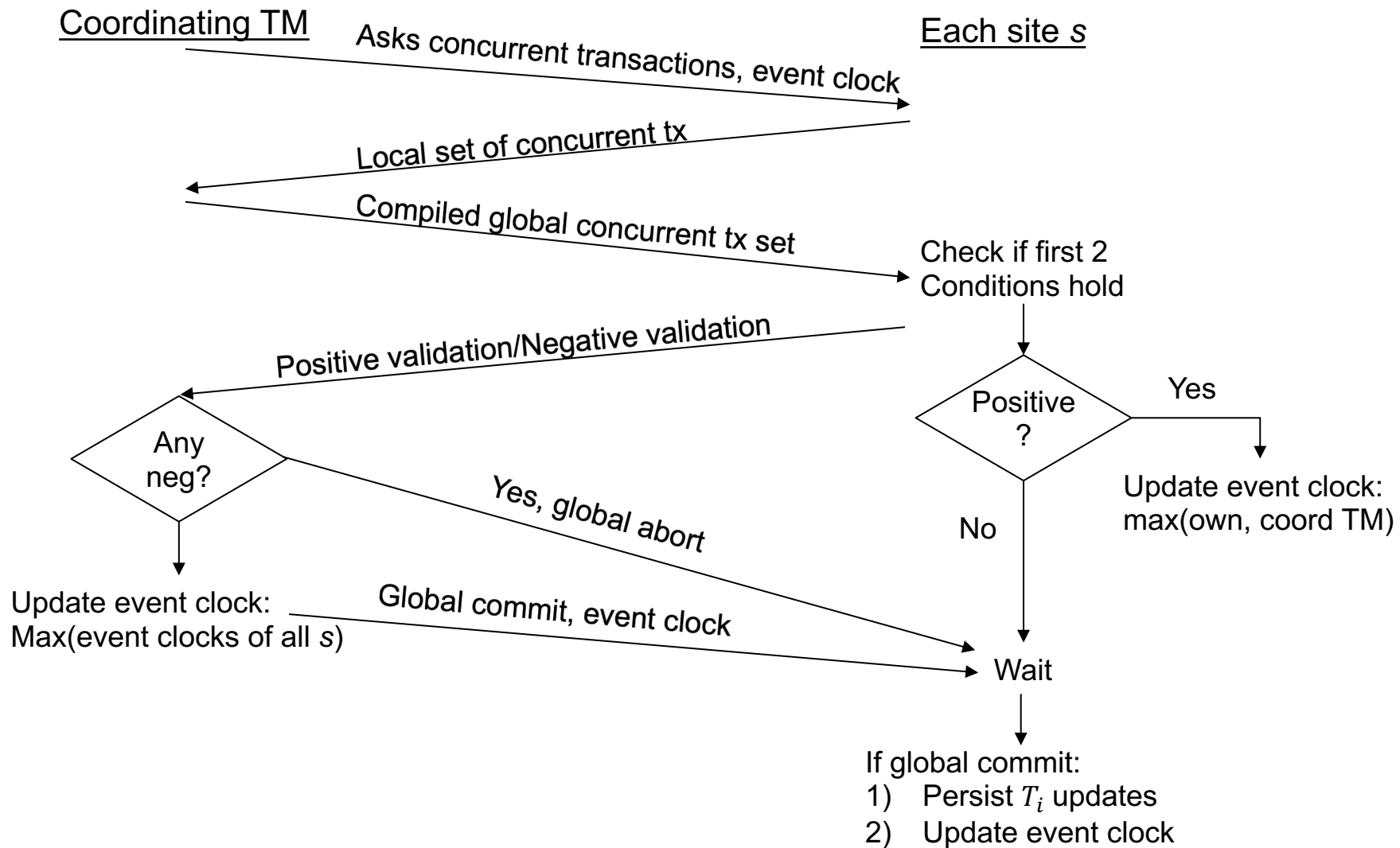
# Snapshot Isolation (SI)

- Each transaction “sees” a consistent snapshot of the database when it starts and R/W this snapshot
- Repeatable reads, but not serializable isolation
- Read-only transactions proceed without significant synchronization overhead
- Centralized SI-based CC
  - 1)  $T_i$  starts, obtains a begin timestamp  $ts_b(T_i)$
  - 2)  $T_i$  ready to commit, obtains a commit timestamp  $ts_c(T_i)$  that is greater than any of the existing  $ts_b$  or  $ts_c$
  - 3)  $T_i$  commits if no other  $T_j$  such that  $ts_c(T_j) \in [ts_b(T_i), ts_c(T_i)]$ ; otherwise aborted (first committer wins)
  - 4) When  $T_i$  commits, changes visible to all  $T_k$  where  $ts_b(T_k) > ts_c(T_i)$

# Distributed CC with SI

- Computing a consistent **distributed** snapshot is hard
- Similar rules to serializability
  - Each local history should be SI
  - Global history is SI  $\rightarrow$  **commitment orders** at each site are the same
- **Dependence relationship**:  $T_i$  at site  $s$ ,  $(T_i^s)$ , is dependent on  $T_j^s$  ( $dependent(T_i^s, T_j^s)$ ) iff
$$(RS(T_i^s) \cap WS(T_j^s) \neq \emptyset) \vee (WS(T_i^s) \cap RS(T_j^s) \neq \emptyset) \vee (WS(T_i^s) \cap WS(T_j^s) \neq \emptyset)$$
- **Conditions**
  - 1)  $dependent(T_i, T_j) \wedge ts_b(T_i^s) < ts_c(T_j^s) \Rightarrow ts_b(T_i^t) < ts_c(T_j^t)$  at every site  $t$  where  $T_i$  and  $T_j$  execute together
  - 2)  $dependent(T_i, T_j) \wedge ts_c(T_i^s) < ts_b(T_j^s) \Rightarrow ts_c(T_i^t) < ts_b(T_j^t)$  at every site  $t$  where  $T_i$  and  $T_j$  execute together
  - 3)  $ts_c(T_i^s) < ts_c(T_j^s) \Rightarrow ts_c(T_i^t) < ts_b(T_j^t)$  at every site  $t$  where  $T_i$  and  $T_j$  execute together

# Distributed CC with SI – Executing $T_i$



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# Outline

- Distributed Transaction Processing
  - ▣ Distributed Concurrency Control
  - ▣ Distributed Reliability

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# Reliability

Problem:

How to maintain

atomicity

durability

properties of transactions

# 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 vs. total failure
- Media failures
  - ❑ Failure of secondary storage devices → 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?
- 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.
- Independent recovery  $\Rightarrow$  non-blocking termination

# Two-Phase Commit (2PC)

*Phase 1* : The coordinator gets the participants ready to write the results into the database

*Phase 2* : Everybody writes the results into the database

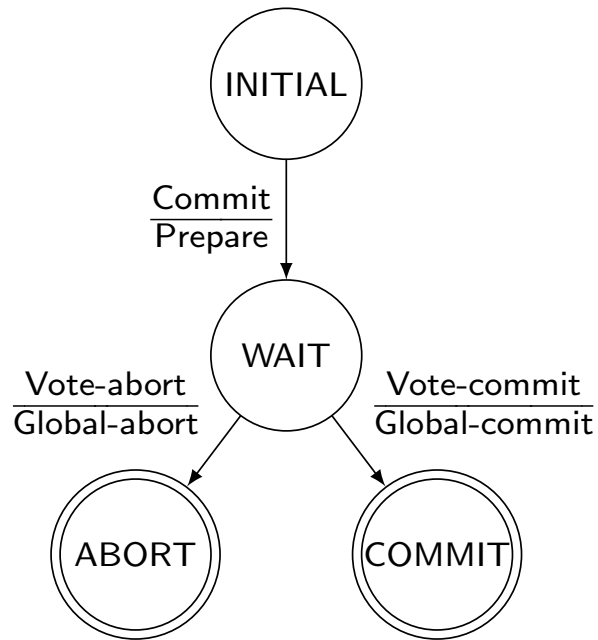
- ❑ **Coordinator** :The process at the site where the transaction originates and which controls the execution
- ❑ **Participant** :The process at the other sites that participate in executing the transaction

## Global Commit Rule:

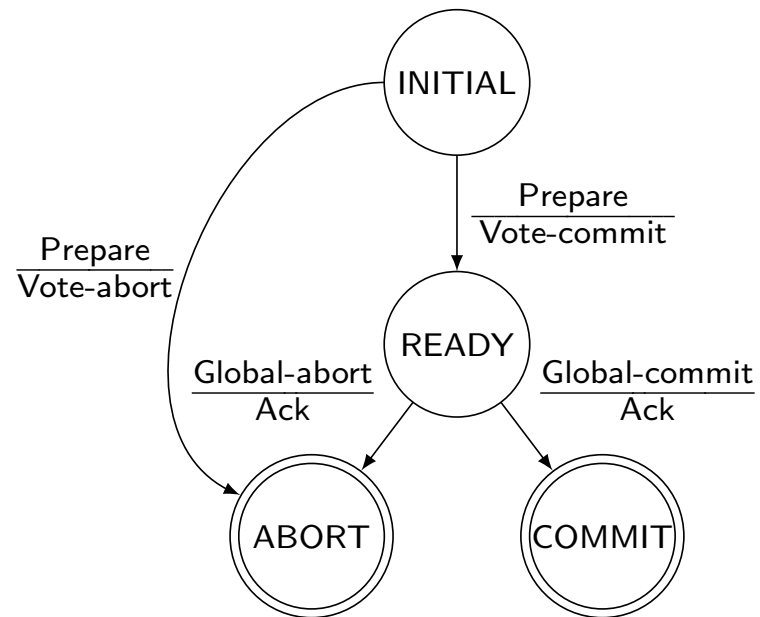
- ❶ The coordinator aborts a transaction if and only if at least one participant votes to abort it.
- ❷ The coordinator commits a transaction if and only if all of the participants vote to commit it.

# State Transitions in 2PC

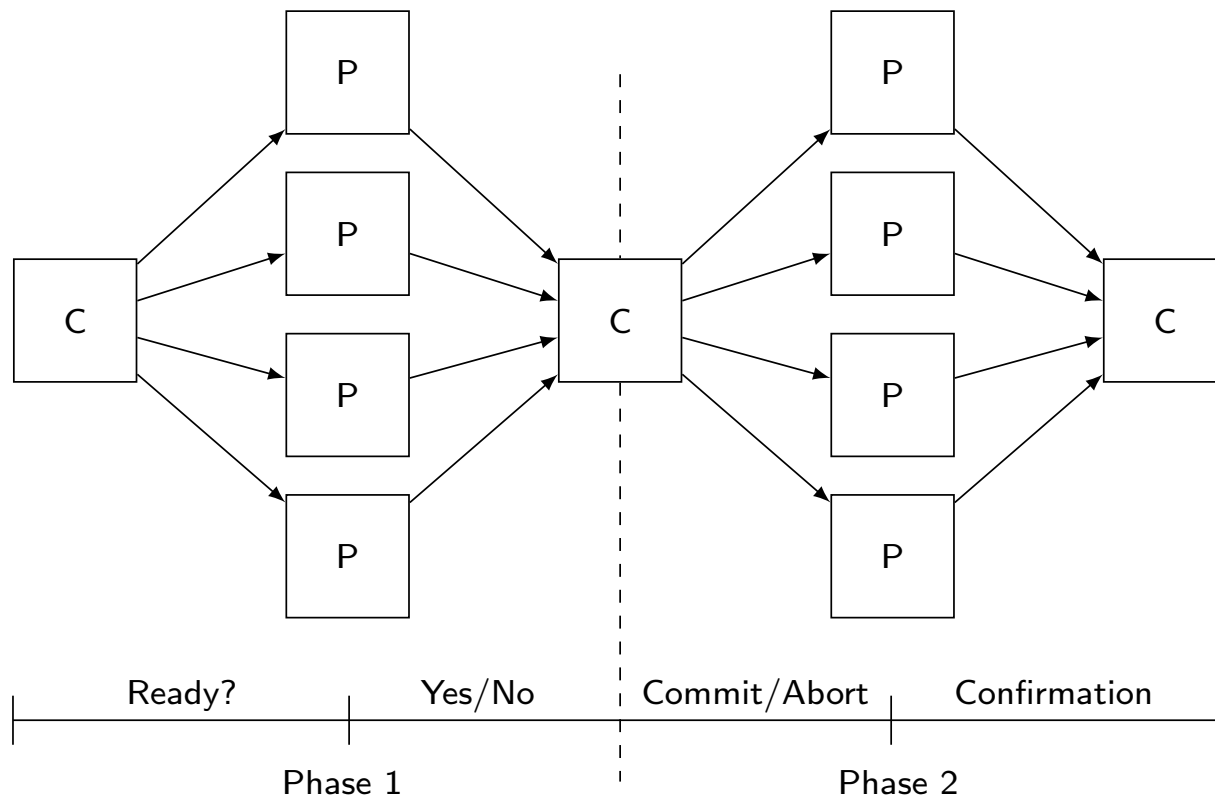
Coordinator



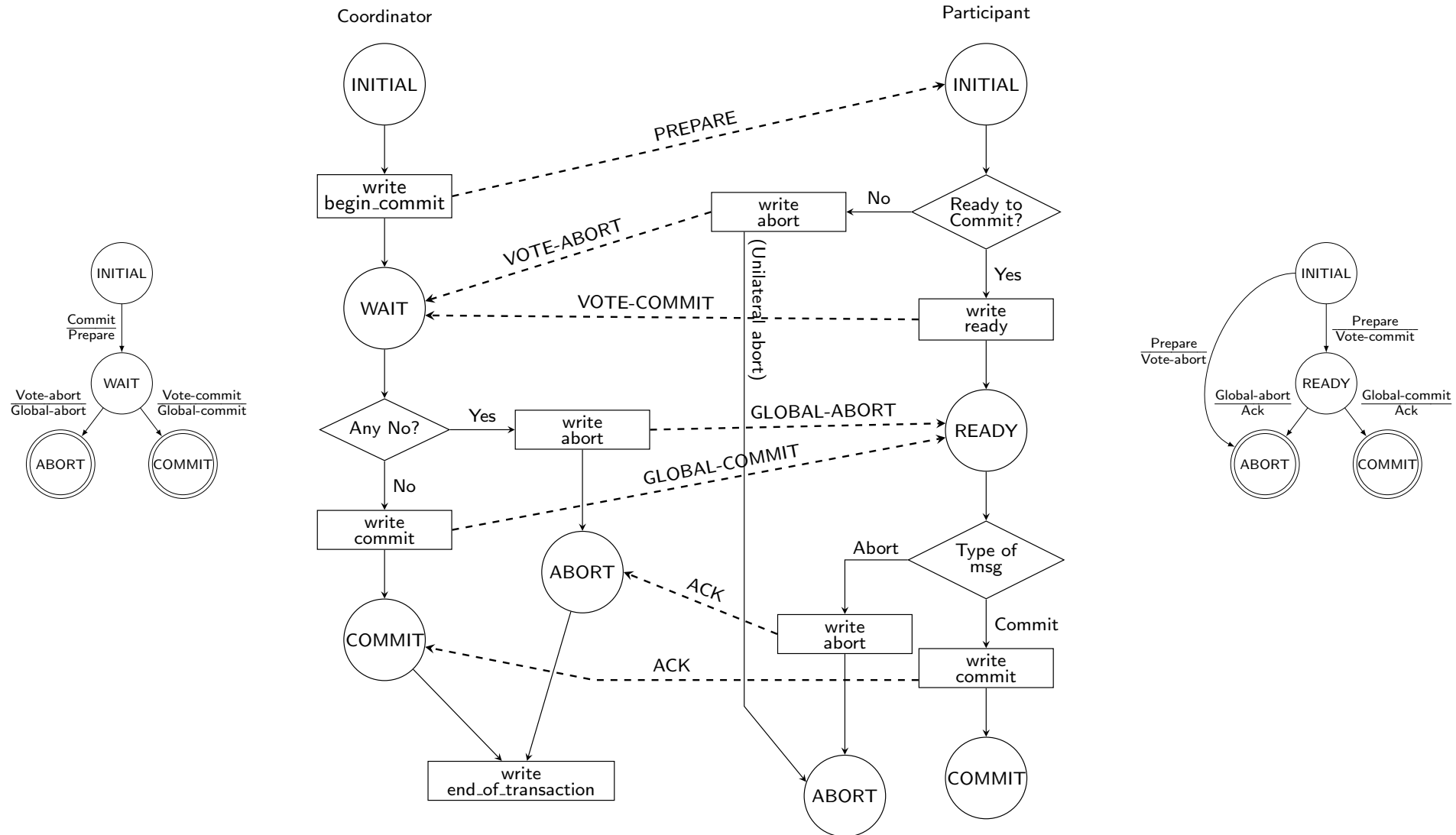
Participant



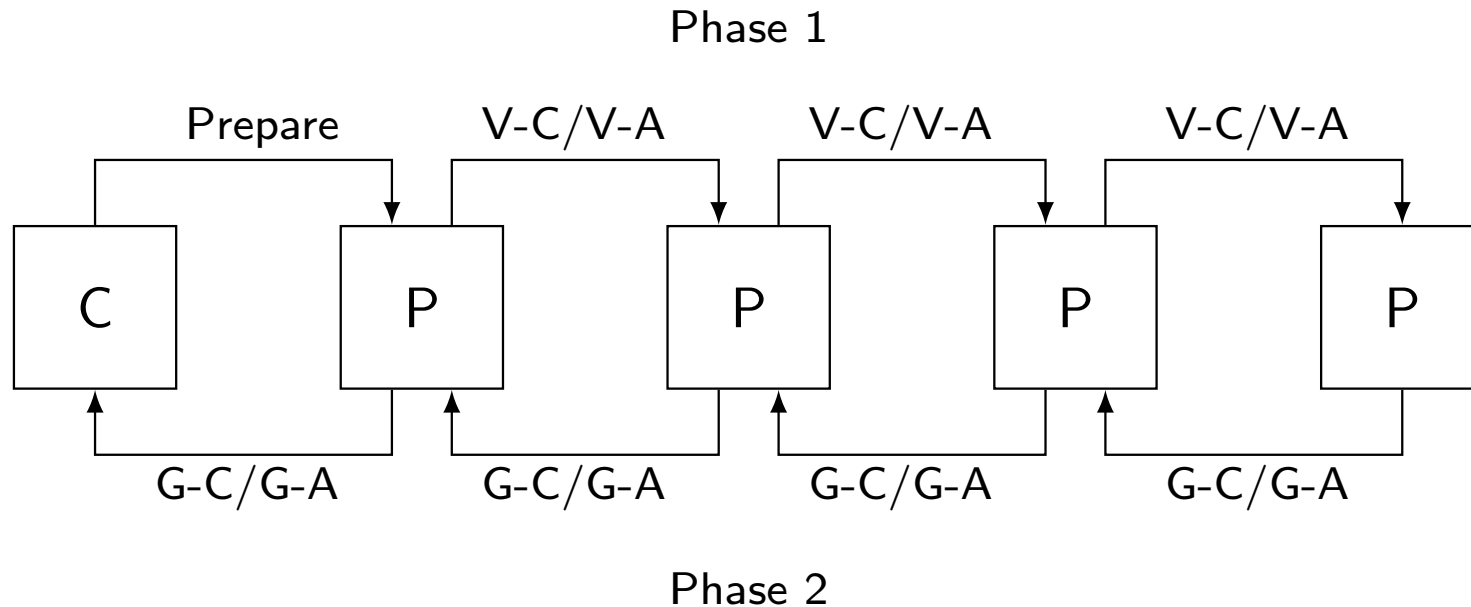
# Centralized 2PC



# 2PC Protocol Actions

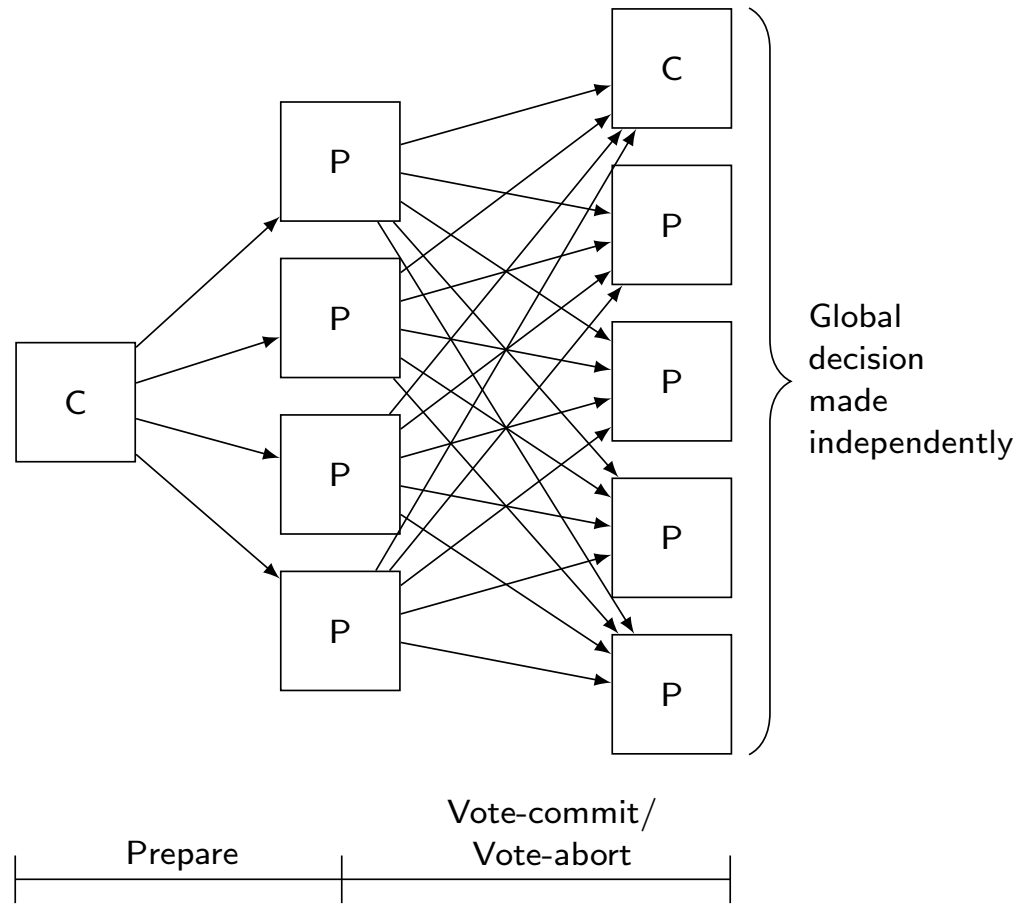


# Linear 2PC



V-C: Vote-Commit, V-A: Vote-Abort, G-C: Global-commit, G-A: Global-abort

# Distributed 2PC



# Variations of 2PC

To improve performance by

- 1) Reduce the number of messages between coordinator & participants
- 2) Reduce the number of time logs are written

## ■ Presumed Abort 2PC

- ❑ Participant polls coordinator about transaction's outcome
- ❑ No information → abort the transaction

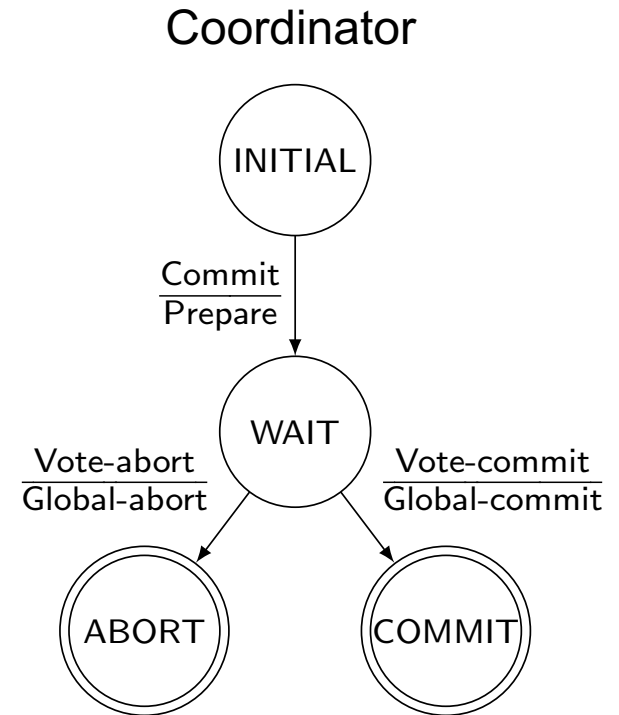
## ■ Presumed Commit 2PC

- ❑ Participant polls coordinator about transaction's outcome
- ❑ No information → assume transaction is committed
- ❑ Not an exact dual of presumed abort 2PC



# 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



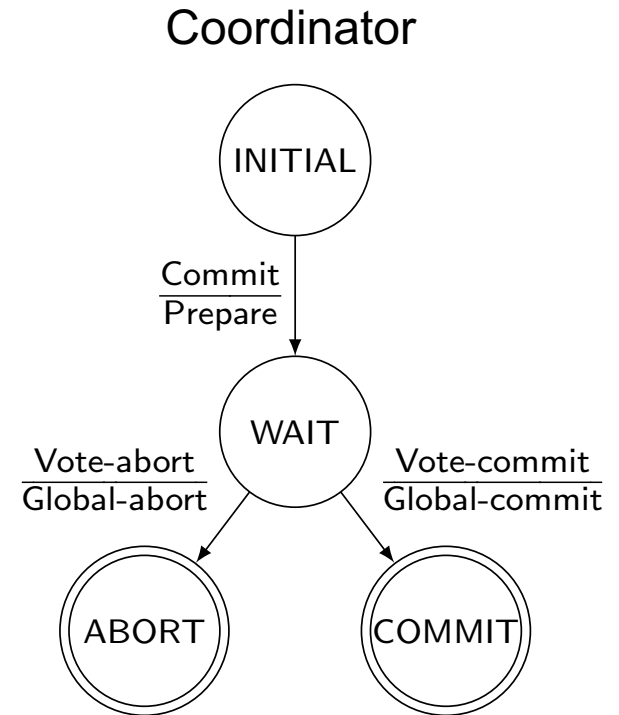
# Site Failures - 2PC Termination

- 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

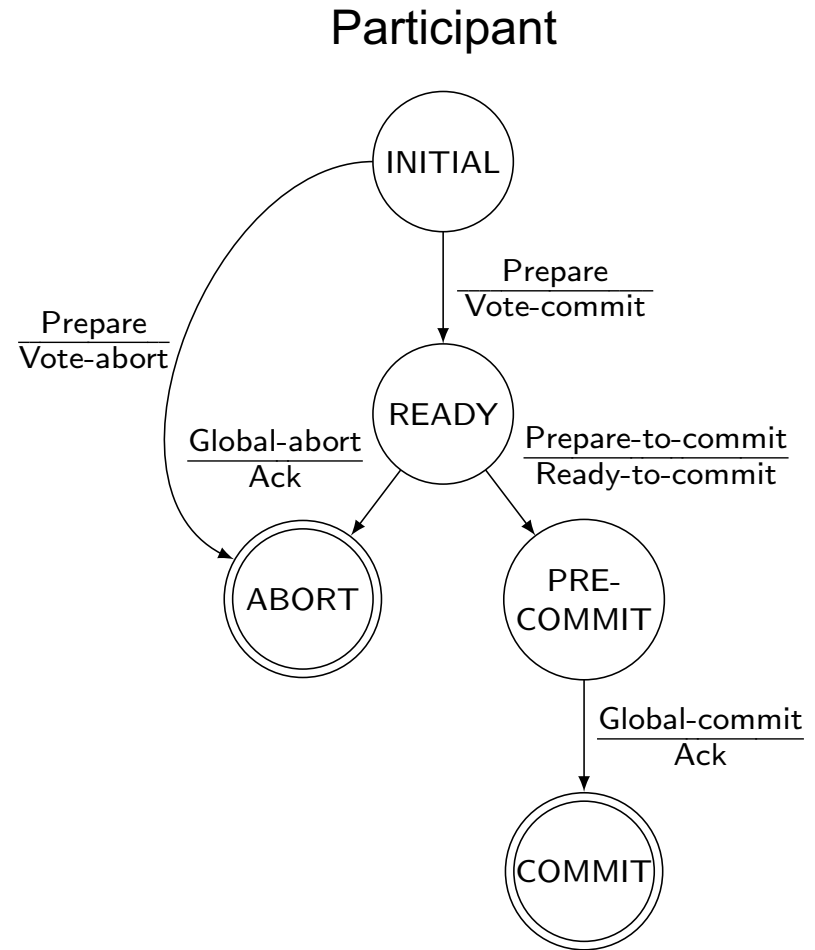
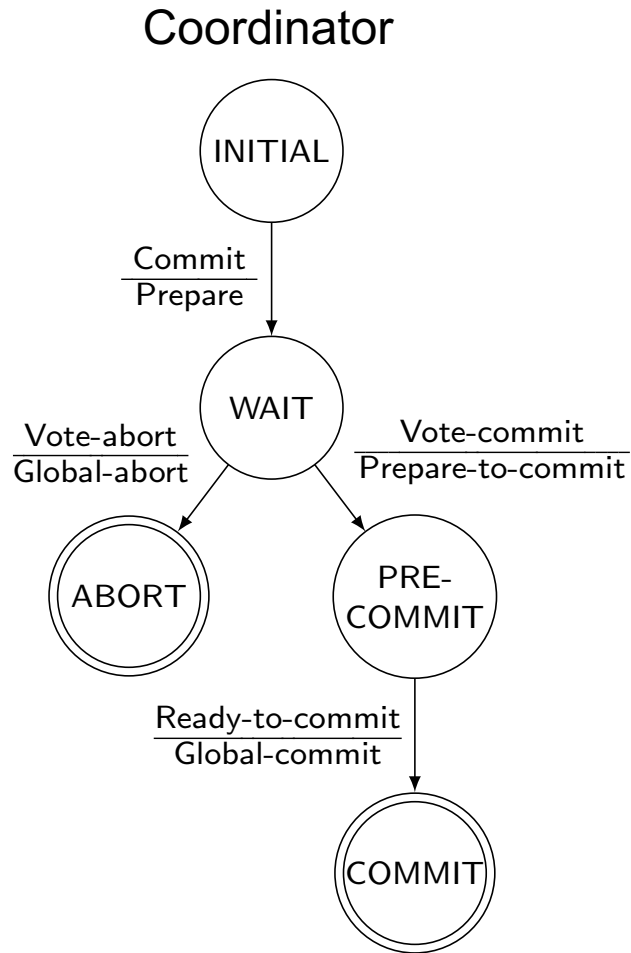
- Blocking
  - Ready implies that the participant waits for the coordinator
  - If coordinator fails, site is blocked until recovery
  - Blocking reduces availability
- Independent recovery is not possible
- However, it is known that:
  - Independent recovery protocols exist only for single site failures;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

# Three-Phase Commit

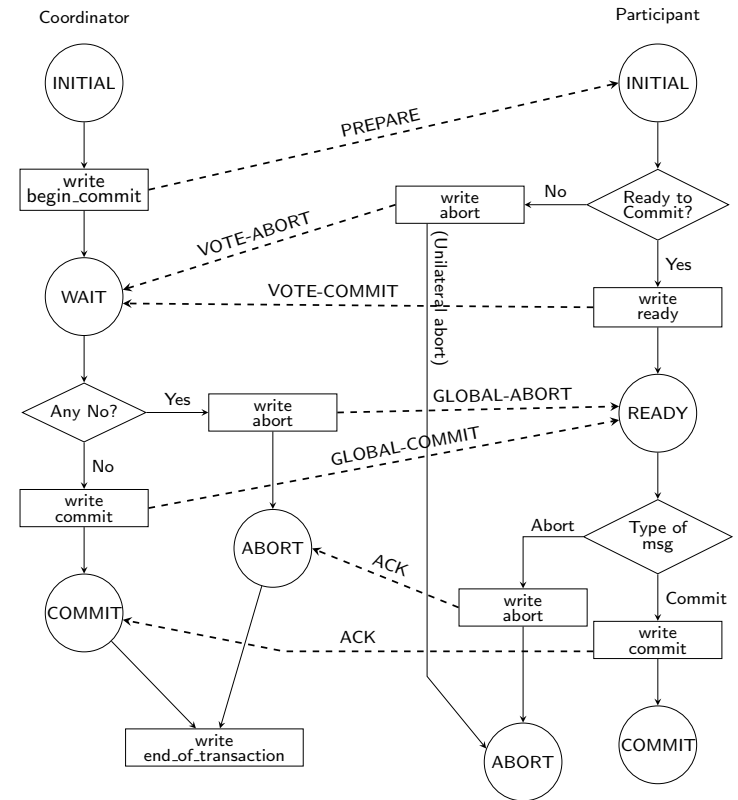
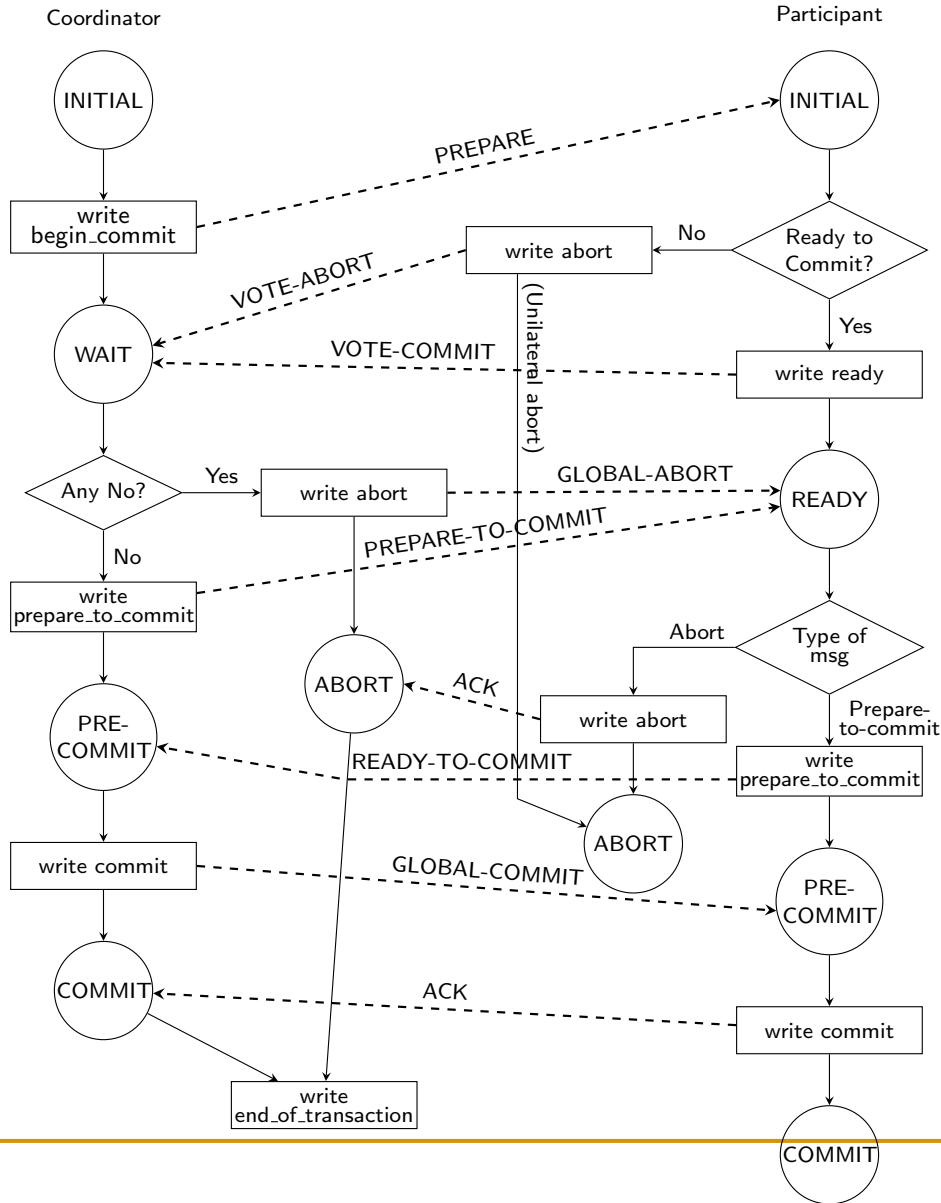
- 3PC is non-blocking.
- A commit protocols is non-blocking iff
  - it is synchronous within one state transition, and
  - its state transition diagram contains
    - no state which is “adjacent” to both a commit and an abort state, and
    - no non-committable state which is “adjacent” to a commit state
- Adjacent: possible to go from one state to another with a single state transition
- Committable: all sites have voted to commit a transaction
  - e.g.: COMMIT state



# State Transitions in 3PC



# 3PC Protocol Actions



# Network Partitioning

- Simple partitioning
  - Only two partitions
- Multiple partitioning
  - More than two partitions
- Formal bounds:
  - There exists no non-blocking protocol that is resilient to a network partition if messages are lost when partition occurs.
  - There exist non-blocking protocols which are resilient to a single network partition if all undeliverable messages are returned to sender.
  - There exists no non-blocking protocol which is resilient to a multiple partition.

# Independent Recovery Protocols for Network Partitioning

- No general solution possible
  - allow one group to terminate while the other is blocked
  - improve availability
- How to determine which group to proceed?
  - The group with a majority
- How does a group know if it has majority?
  - Centralized
    - Whichever partitions contains the central site should terminate the transaction
  - Voting-based (quorum)

# Quorum Protocols

- 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  $V_a$

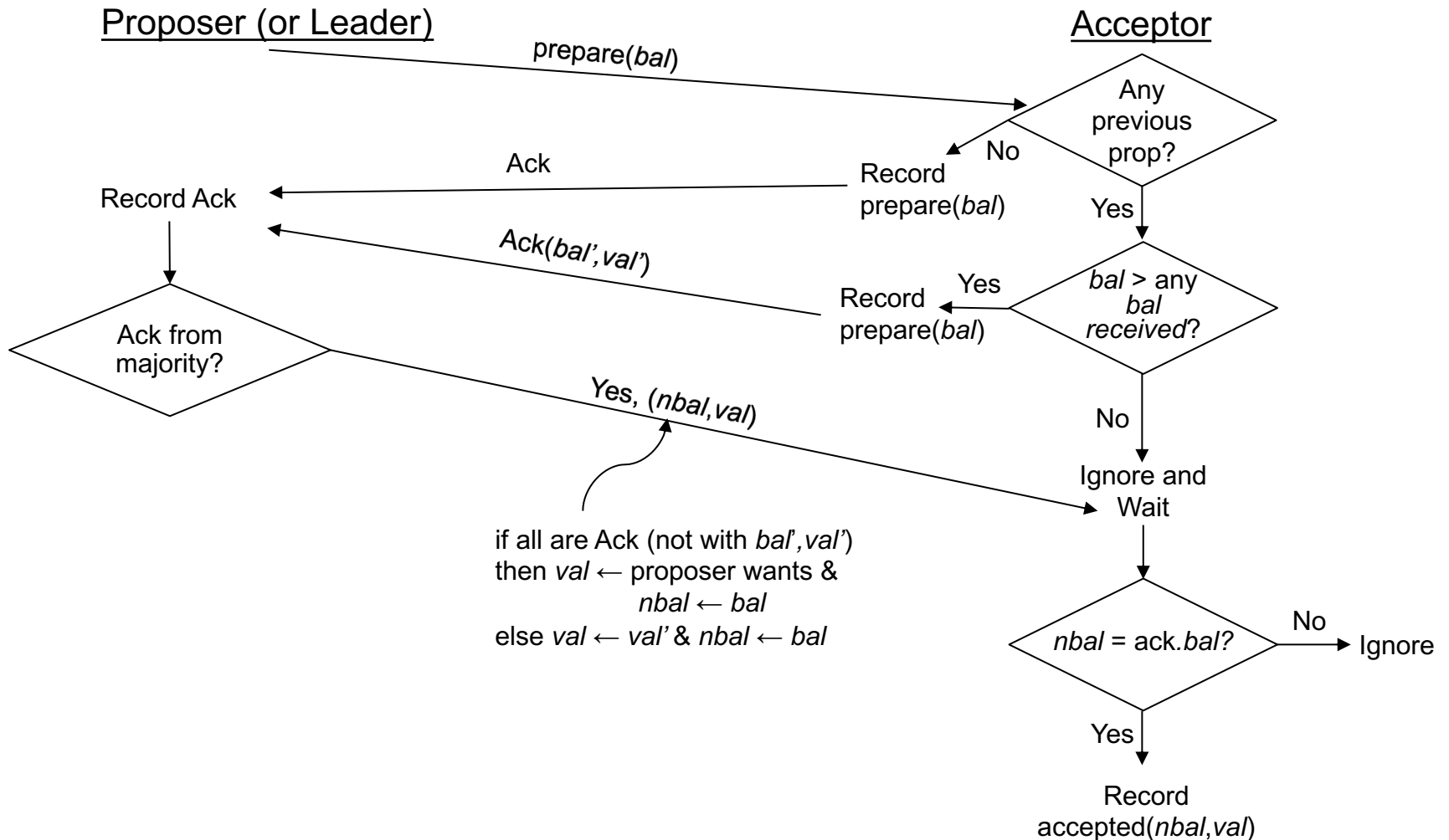
# Paxos Consensus Protocol

- General problem: how to reach an agreement (consensus) among TMs about the fate of a transaction
  - 2PC and 3PC are special cases
- General idea: If a majority reaches a decision, the global decision is reached (like voting)
- Roles:
  - Proposer: recommends a decision
  - Acceptor: decides whether to accept the proposed decision
  - Learner: discovers the agreed-upon decision by asking or it is pushed

# Paxos & Complications

- Naïve Paxos: one proposer
  - Operates like a 2PC
- Complications
  - Multiple proposers can exist at the same time; acceptor has to choose
    - Attach a ballot number
  - Multiple proposals may result in split votes with no majority
    - Run multiple consensus rounds → performance implication
    - Choose a leader
  - Some accepts fail after they accept a decision; the remaining acceptors may not constitute majority
    - Use ballot numbers

# Basic Paxos – No Failures





# Basic Paxos with Failures

- Some acceptors fail but there is quorum
  - ▣ Not a problem
- Enough acceptors fail to eliminate quorum
  - ▣ Run a new ballot
- Proposer/leader fails
  - ▣ Choose a new leader and start a new ballot