Transactions & Concurrency

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Transactions

- Series of operations executed by client
- Each operation is an RPC to a server
- A transaction either
  - completes and *commits* all its operations at server
    - Commit = reflect updates on server-side objects
  - Or *aborts* and has no effect on server

Transactions

- Motivation
  - Provide **atomic** operations at servers that maintain shared data for clients
  - Provide **recoverability** from server crashes
- Properties
  - Atomicity, Consistency, Isolation, Durability (ACID)
- Concepts: commit, abort

ACID properties for transactions

- **Atomicity**: All or nothing
- **Consistency**: if the server starts in a consistent state, the transaction ends the server in a consistent state.
- **Isolation**: Each transaction must be performed *without interference* from other transactions, i.e., non-final effects of a transaction must not be visible to other transactions.
  - No access to intermediate results/states of other transactions
  - Free from interference by operations of other transactions
- **Durability**: After a transaction has completed successfully, all its effects are saved in permanent storage.

Operations of the *Account* interface

deposit(amount)
deposit amount in the account
withdraw(amount)
withdraw amount from the account
getBalance() -> amount
return the balance of the account
setBalance(amount)
set the balance of the account to amount

Operations of the Branch interface

create(name) -> account
create a new account with a given name
lookUp(name) -> account
return a reference to the account with the given name
branchTotal() -> amount
return the total of all the balances at the branch

A client's banking transaction

Transaction T:
a.withdraw(100);
b.deposit(100);
c.withdraw(200);
b.deposit(200);

Operations in *Coordinator* interface

openTransaction( ) → *trans;*

starts a new transaction and delivers a unique TID *trans*. This identifier will be used in the other operations in the transaction.

closeTransaction(trans) → *(commit, abort);*

ends a transaction: a *commit* return value indicates that the transaction has committed; an *abort* return value indicates that it has aborted.

abortTransaction(trans);

aborts the transaction.

Transaction life histories

Successful	*Aborted by client*	*Aborted by server*	
openTransaction *operation* *operation* ⋮ *operation* *closeTransaction*	*openTransaction* *operation* *operation* ⋮ *operation* *abortTransaction*	server aborts transaction →	*openTransaction* *operation* *operation* ⋮ *operation ERROR reported to client*

Multiple clients, one server

- What could go wrong?

The lost update problem

Transaction *T*:		**Transaction *U*:**	
balance = b.getBalance();		*balance = b.getBalance();*	
*b.setBalance(balance*1.1);*		*b.setBalance(balance*1.1);*	
a.withdraw(balance/10)		*c.withdraw(balance/10)*	
balance = b.getBalance();	$200		
		balance = b.getBalance();	$200
		*b.setBalance(balance*1.1);*	$220
*b.setBalance(balance*1.1);*	$220		
a.withdraw(balance/10)	$80		
		U's update is overwritten by T	
		c.withdraw(balance/10)	$280

Initially, A's balance is $100, B's balance is $200, and C's balance is $300.

The inconsistent retrievals problem

Transaction *V*		**Transaction *W*:**	
a.withdraw(100) *b.deposit(100)*		*aBranch.branchTotal()*	
a.withdraw(100);	$100		
		total = a.getBalance()	$100
		total = total+b.getBalance()	$300
		total = total+c.getBalance()	Total has the wrong value!
b.deposit(100)	$300	⋮	

Initially, A's balance is $200, and B's balance is also $200.

- How to prevent transactions from affecting each other?

Concurrent transactions

- A naïve approach:
  - Executes one transaction a time at the server
  - But reduces the number of concurrent transactions
  - Transactions per second directly related to the revenue of companies
- Goal: increase concurrency while maintaining ACID.

Concurrency control

- Motivation: without concurrency control, we have *lost updates*, *inconsistent retrievals,* etc.
- Concurrency control schemes are designed to allow two or more transactions to be executed concurrently while maintaining **serial equivalence**
  - Serial equivalence is correctness criterion
    - Schedule produced by concurrency control scheme should be equivalent to a serial schedule in which transactions are executed one after the other
- Schemes: locking, optimistic concurrency control, time-stamp based concurrency control

A serially equivalent interleaving of *T* and *U*

Transaction *T*		**Transaction *U***	
balance = b.getBalance()		*balance = b.getBalance()*	
*b.setBalance(balance*1.1)*		*b.setBalance(balance*1.1)*	
a.withdraw(balance/10)		*c.withdraw(balance/10)*	
balance = b.getBalance()	$200		
*b.setBalance(balance*1.1)*	$220		
		balance = b.getBalance()	$220
		*b.setBalance(balance*1.1)*	$242
a.withdraw(balance/10)	$80		
		c.withdraw(balance/10)	$278

A serially equivalent interleaving of V and W

Transaction *V*:		**Transaction *W*:**	
a.withdraw(100);		*aBranch.branchTotal()*	
b.deposit(100)			
a.withdraw(100);	$100		
b.deposit(100)	$300		
		total = a.getBalance()	$100
		total = total+b.getBalance()	$400
		total = total+c.getBalance()	
		...	

Read and *write* operation conflict rules

Operations of different transactions		*Conflict*	*Reason*
read	*read*	No	Because the effect of a pair of *read* operations does not depend on the order in which they are executed
read	*write*	Yes	Because the effect of a *read* and a *write* operation depends on the order of their execution
write	*write*	Yes	Because the effect of a pair of *write* operations depends on the order of their execution

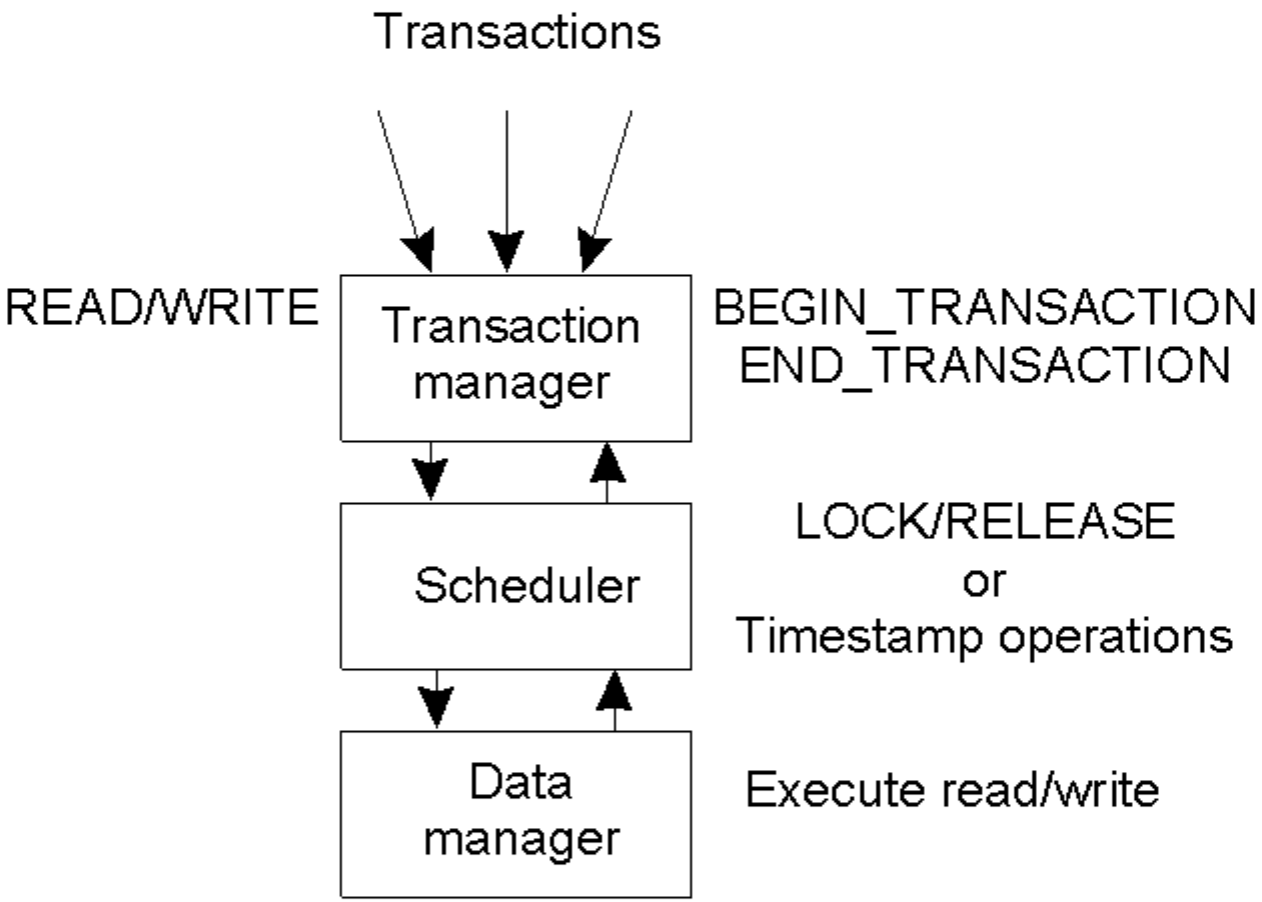
Checking for serial equivalence

- Two transactions are serially equivalent if and only if all pairs of **conflicting operations** (pair containing one operation from each transaction) are executed in the **same order** (transaction order) for all objects (data) they both access.
  - Take all pairs of conflict operations, one from T and one from U
  - If the T operation was reflected first on the server, mark the pair as “(T, U)”, otherwise mark it as “(U, T)”
  - All pairs should be marked as either “(T, U)” or all pairs should be marked as “(U, T)”.

A non-serially equivalent interleaving of operations of transactions T and U

Transaction *T*:	**Transaction *U*:**
x = read(i)	
write(i, 10)	
	y = read(j)
	write(j, 30)
write(j, 20)	
	z = read (i)

Concurrency control



General organization of managers for handling transactions.

Lock compatibility

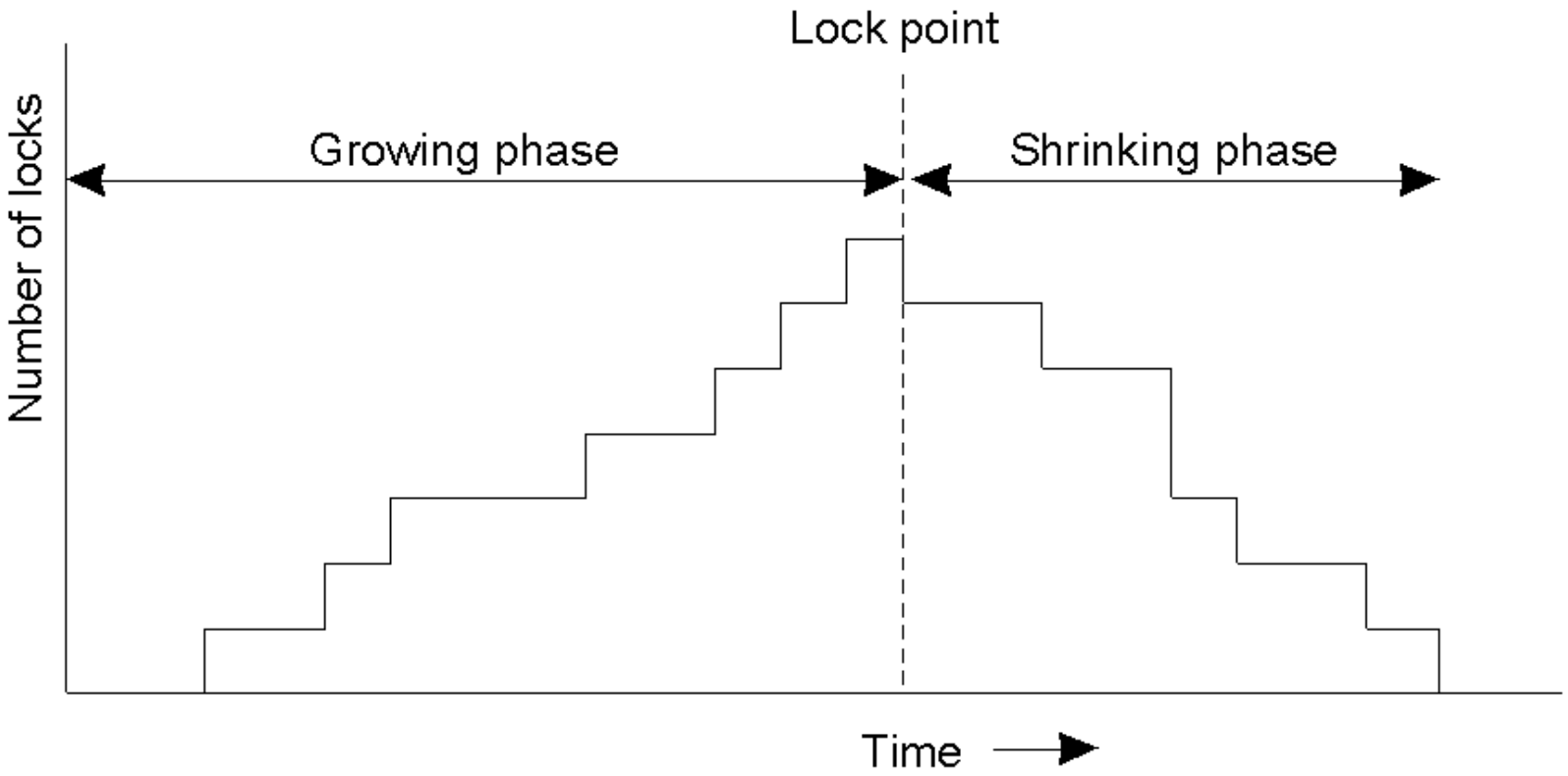
For one object		*Lock requested*	
		read	*write*
Lock already set	*none*	OK	OK
	read	OK	wait
	write	wait	wait

Transactions *T* and *U* with exclusive locks

Transaction ***T*** **:**		**Transaction** ***U*** **:**	
balance = b.getBalance() *b.setBalance(bal*1.1)* *a.withdraw(bal/10)*		*balance = b.getBalance()* *b.setBalance(bal*1.1)* *c.withdraw(bal/10)*	
Operations	Locks	Operations	Locks
openTransaction			
bal = b.getBalance()	lock *B*		
*b.setBalance(bal*1.1)*		*openTransaction*	
a.withdraw(bal/10)	lock *A*	*bal = b.getBalance()*	waits for *T*'s lock on *B*
closeTransaction	unlock *A*, *B*	• • •	
			lock *B*
		*b.setBalance(bal*1.1)*	
		c.withdraw(bal/10)	lock *C*
		closeTransaction	unlock *B*, *C*

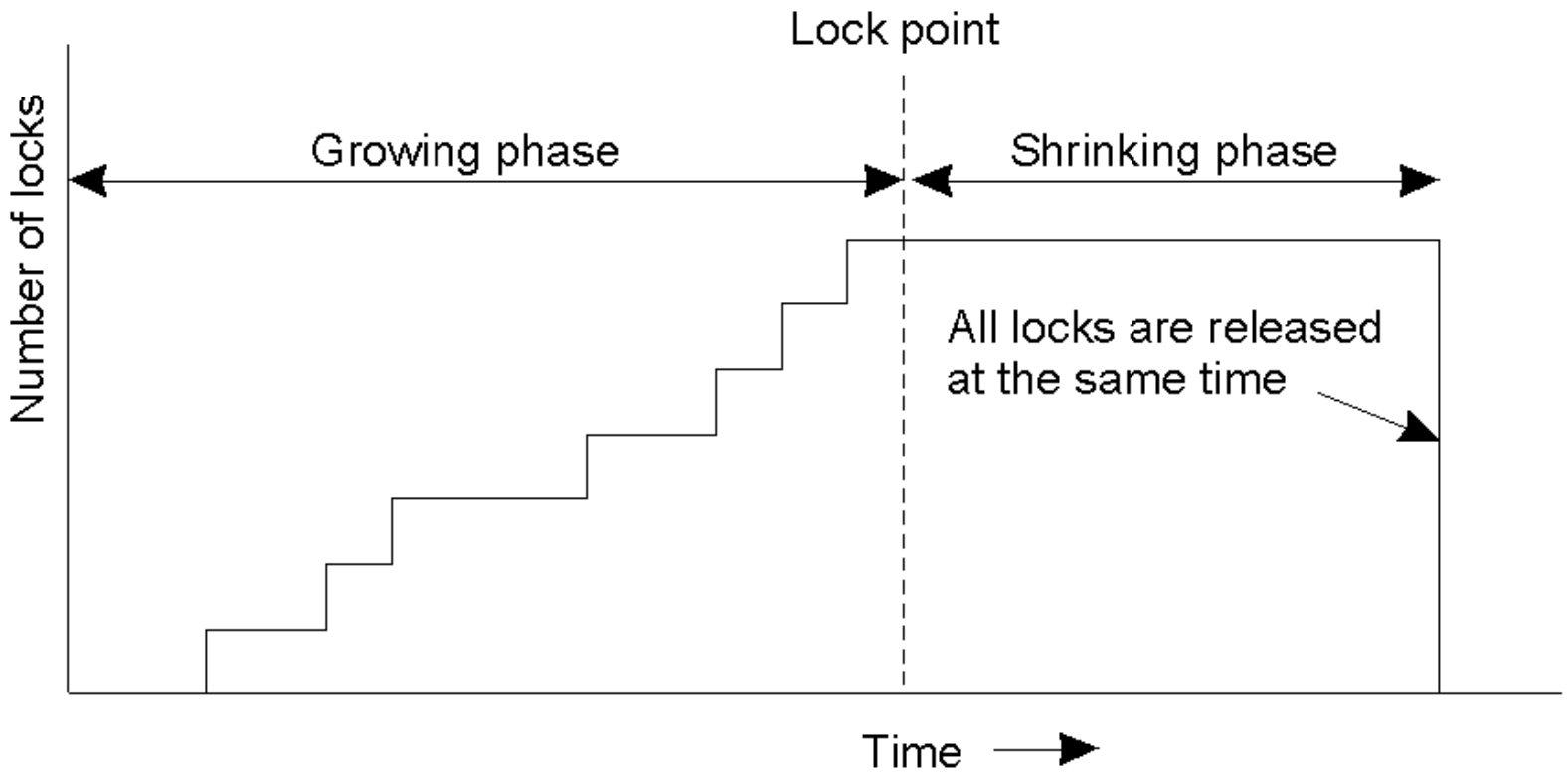
Two-Phase Locking

- Two-phase locking



Strict Two-Phase Locking

- Strict two-phase locking.



Use of locks in strict two-phase locking

1. When an operation accesses an object within a transaction:

   (a) If the object is not already locked, lock it and the operation proceeds.

   (b) If the object has a conflicting lock set by another transaction, the transaction must wait until it is unlocked.

   (c) If the object has a non-conflicting lock set by another transaction, the lock is shared and the operation proceeds.

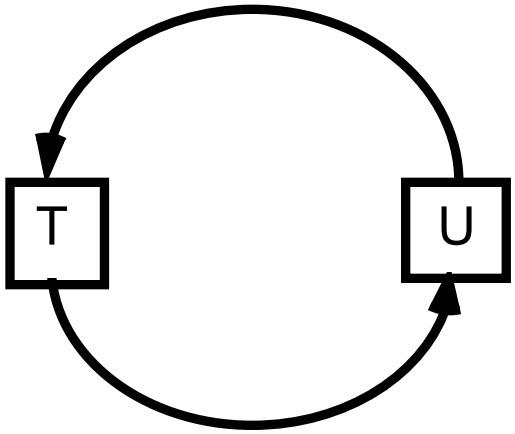
   (d) If the object has already been locked in the same transaction, the lock will be promoted if necessary and the operation proceeds. (Where promotion is prevented by a conflicting lock, rule (b) is used.)

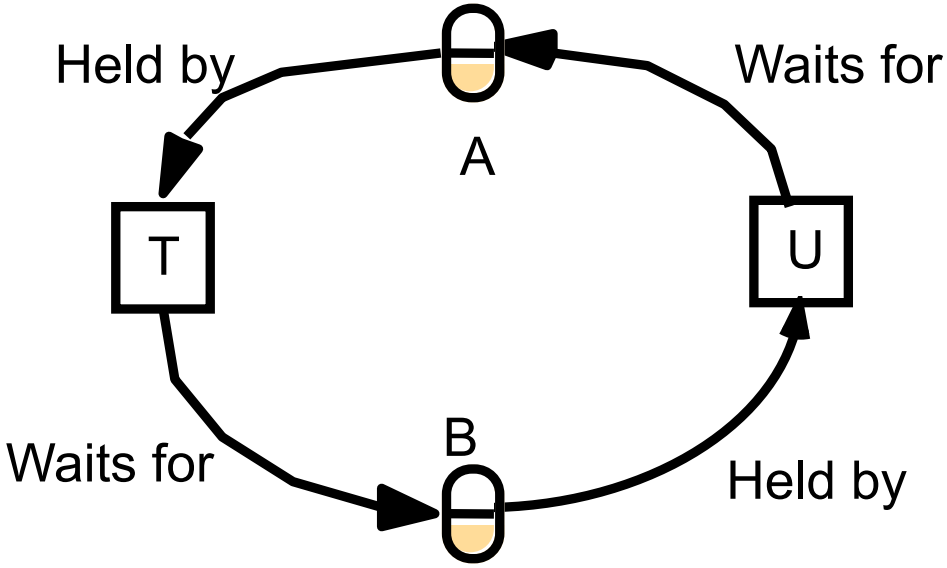
2. When a transaction is committed or aborted, the server unlocks all objects it locked for the transaction.

Deadlock with write locks

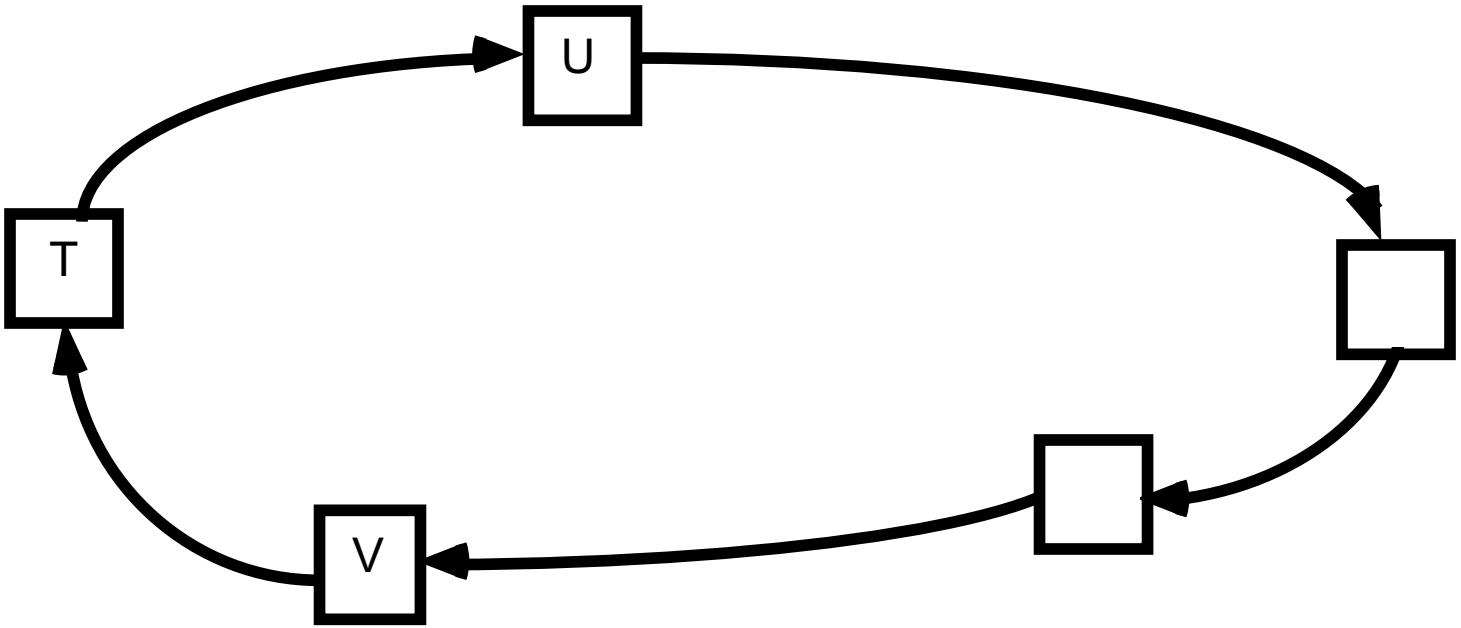
Transaction *T*		Transaction *U*	
Operations	**Locks**	**Operations**	**Locks**
a.deposit(100);	write lock *A*		
		b.deposit(200)	write lock *B*
b.withdraw(100)			
•••	waits for *U*'s	*a.withdraw(200);*	waits for *T*'s
	lock on *B*	•••	lock on *A*
•••		•••	
•••		•••	

The wait-for graph

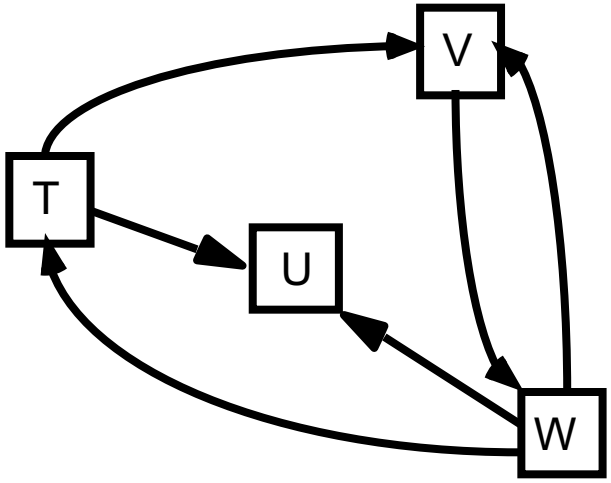


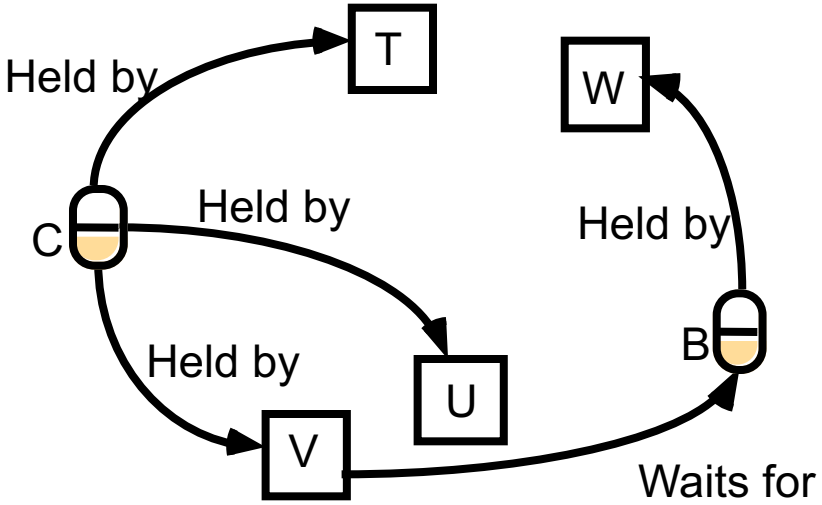


A cycle in a wait-for graph



Another wait-for graph





T/U/V share a read lock on object C.
W holds a write lock on B, on which V is waiting to obtain a lock.
T/W then request write locks on object C.
Deadlock: T waits for U/V, V waits for W, W waits for T/U/V.

Resolution of deadlock

Transaction T		Transaction U	
Operations	**Locks**	**Operations**	**Locks**
a.deposit(100);	write lock *A*		
		b.deposit(200)	write lock *B*
b.withdraw(100)			
•••	waits for *U*'s lock on *B*	*a.withdraw(200);*	waits for T's lock on *A*
	(timeout elapses)	•••	
T's lock on *A* becomes vulnerable, unlock *A*, abort T		•••	
		a.withdraw(200);	write locks *A* unlock *A*, *B*

Drawbacks of locking

- Overhead of lock maintenance
- Deadlocks
- Reduced concurrency
  - e.g., a transaction has to hold the lock until the transaction finishes even if not going to use it

Optimistic concurrency control

- In most applications, likelihood of conflicting accesses by concurrent transactions is low
- Transactions proceed as though there are no conflicts
  - read and write objects at will
  - **check for serial equivalence at *commit time***
- Three phases
  - **Working Phase** – transactions read and write private copies of objects
  - **Validation Phase** – each transaction is assigned a transaction number when it enters this phase
  - **Update Phase**

Optimistic concurrency control

- Increases concurrency more than pessimistic concurrency control (locking)
- Increases transactions per second
- For non-transaction systems, increases operations per second and lowers latency
- Preferable than pessimistic when conflicts are expected to be rare
  - But still need to ensure conflicts are caught!

Optimistic concurrency control: serializability of transaction T_v w.r.t. T_i

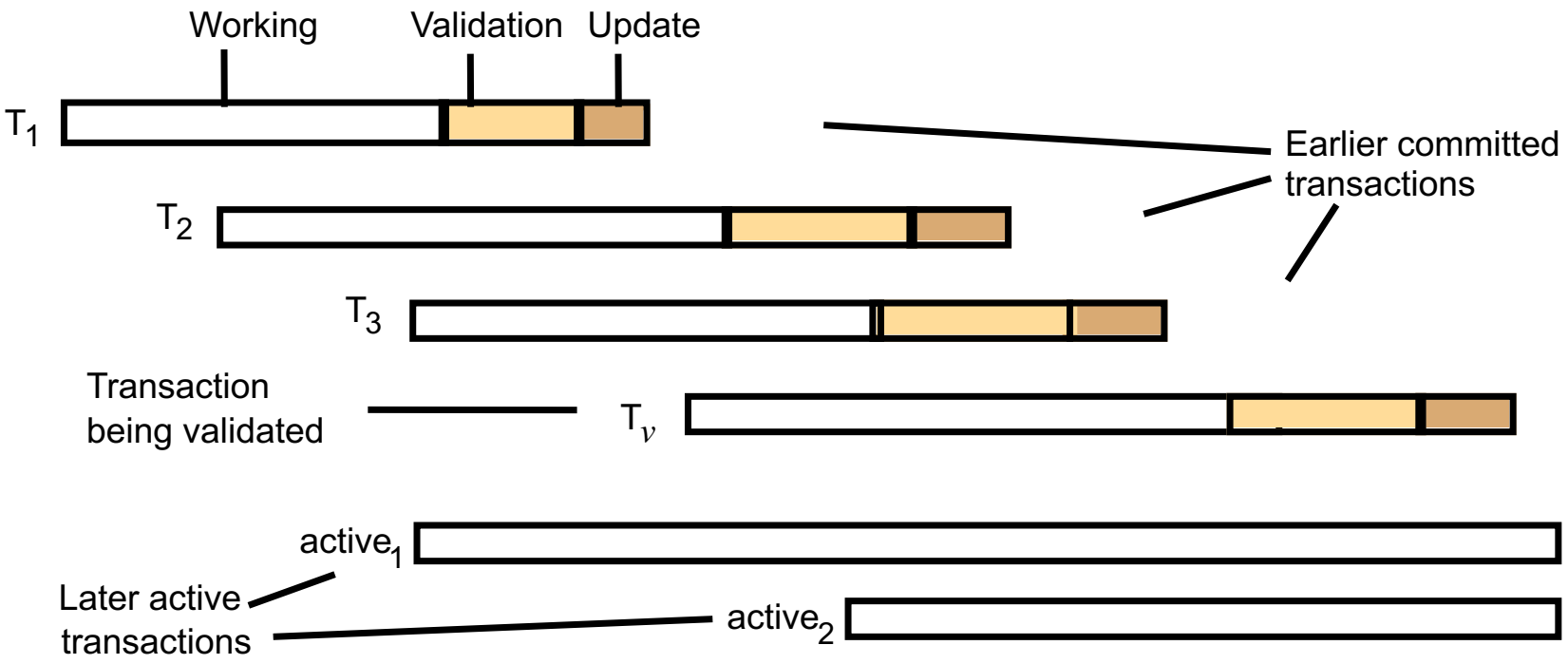
T_v and T_i are overlapping transactions

For T_v to be serializable w.r.t T_i the following rules must hold

T_v	T_i	*Rule*
write	*read*	1. T_i must not read objects written by T_v
read	*write*	2. T_v must not read objects written by T_i
write	*write*	3. T_i must not write objects written by T_v and T_v must not write objects written by T_i

If simplification is made that only one transaction may be in its validation or write/update phases at one time, then third rule is always satisfied

Validation of transactions



Earlier committed transactions are $T_1/T_2/T_3$.
T_1 committed before T_v started. T_2 and T_3 committed before T_v finished its working phase.

Validation of transactions

Backward validation of transaction T_v

```
boolean valid = true;
for (int T_i = startTn+1; T_i <= finishTn; T_i++){
    if (read set of T_v intersects write set of T_i) valid = false;
}
```

startTn is the biggest transaction number assigned to some other committed transaction at the time when T_v started its working phase

finishTn is the biggest transaction number assigned when T_v entered the validation phase.

Validation of transactions

Forward validation of transaction T_v

```
boolean valid = true;
for (int T_id = active1; T_id <= activeN; T_id++){
    if (write set of T_v intersects read set of T_id) valid = false;
}
```

active1 ... N are overlapping active transactions that are still in their working phase.

Timestamp based concurrency control

- Each transaction is assigned a *unique* timestamp at the moment it starts
  - In distributed transactions, Lamport timestamps can be used
- This timestamp determines the transaction's position in serialization order
- Every data item has a timestamp
  - Read timestamp = timestamp of transaction that last read the item
  - Write timestamp = timestamp of transaction that most recently changed an item

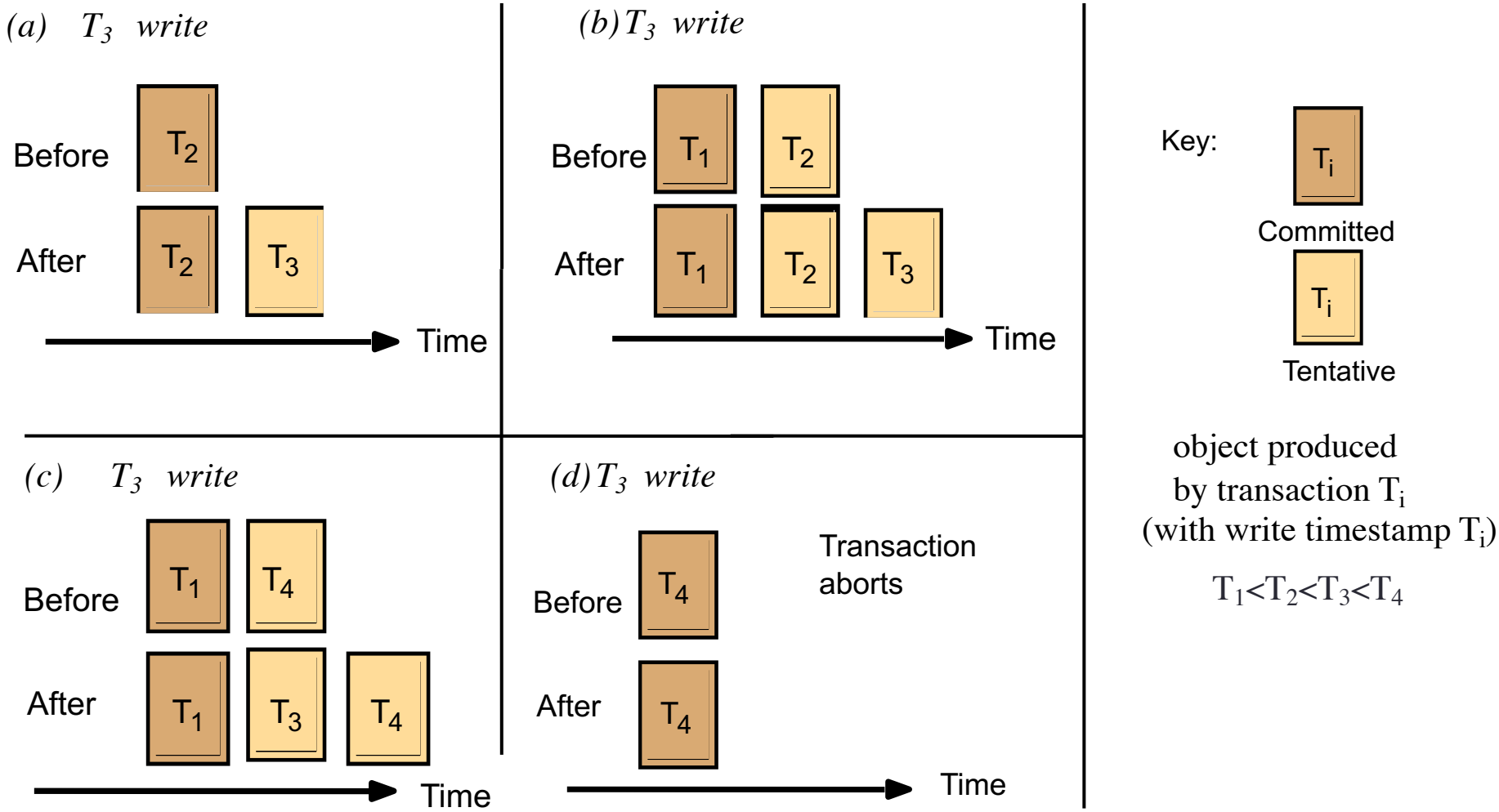
Operation conflicts for timestamp ordering

Rule	T_c	T_i	
1.	*write*	*read*	T_c must not *write* an object that has been *read* by any T_i where $T_i > T_c$ this requires that $T_c \geq$ the maximum read timestamp of the object.
2.	*write*	*write*	T_c must not *write* an object that has been *written* by any T_i where $T_i > T_c$ this requires that $T_c >$ write timestamp of the committed object.
3.	*read*	*write*	T_c must not *read* an object that has been *written* by any T_i where $T_i > T_c$ this requires that $T_c >$ write timestamp of the committed object.

Timestamp ordering *write* rule

if ($T_c \geq$ maximum read timestamp on D &&
    $T_c >$ write timestamp on committed version of D)
        perform write operation on tentative version of D with write timestamp T_c
else /* write is too late */
    Abort transaction T_c

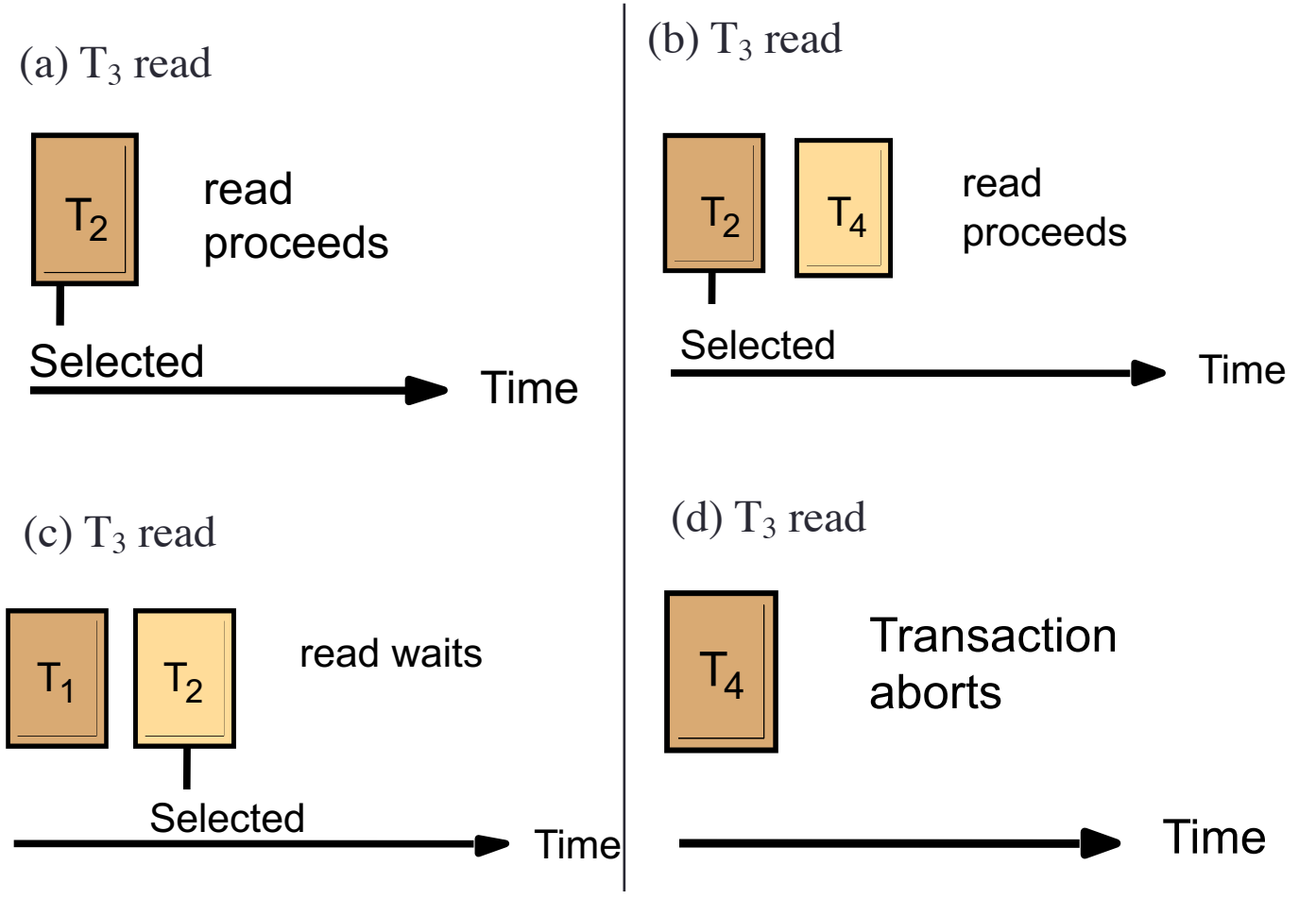
Write operations and timestamps



Timestamp ordering *read* rule

if (T_c > write timestamp on committed version of D) {
    let D_{selected} be the version of D with the maximum write timestamp ≤ T_c
    if (D_{selected} is committed)
        perform *read* operation on the version D_{selected}
    else
        Wait until the transaction that made version D_{selected} commits or aborts
        then reapply the *read* rule
} else
    Abort transaction T_c

Read operations and timestamps



Timestamps in transactions *T* and *U*

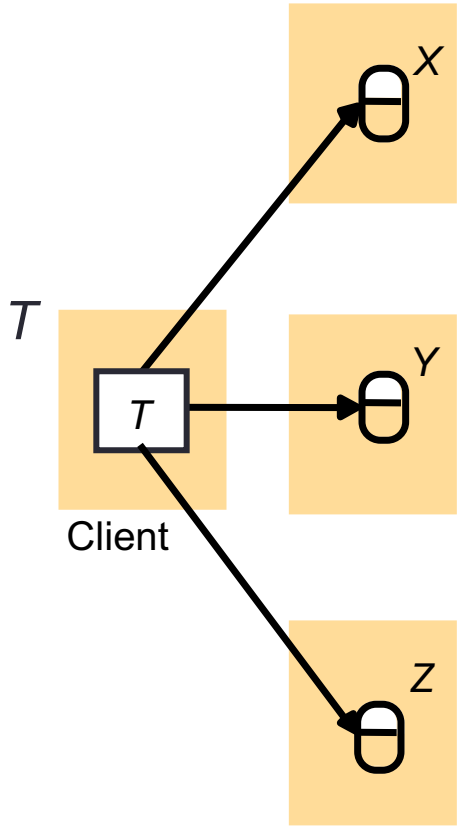
T	*U*	*Timestamps and versions of objects* A RTS	A WTS	B RTS	B WTS	C RTS	C WTS
		{}	**S**	{}	**S**	{}	**S**
openTransaction							
bal = b.getBalance()				{*T*}			
	openTransaction						
*b.setBalance(bal*1.1)*					**S**, *T*		
	bal = b.getBalance()						
	wait for T						
a.withdraw(bal/10)	● ● ●		**S**, *T*				
commit	● ● ●		***T***		***T***		
	bal = b.getBalance()			{*U*}			
	*b.setBalance(bal*1.1)*				***T***, *U*		
	c.withdraw(bal/10)						**S**, *U*

Timestamps of committed transactions are in BOLD

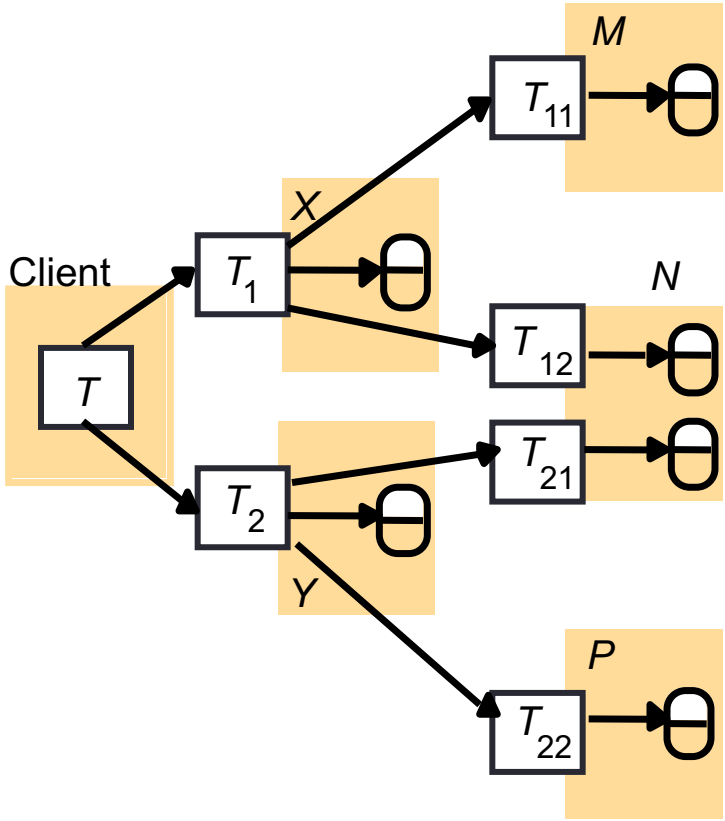
Distributed Transactions

Distributed transactions

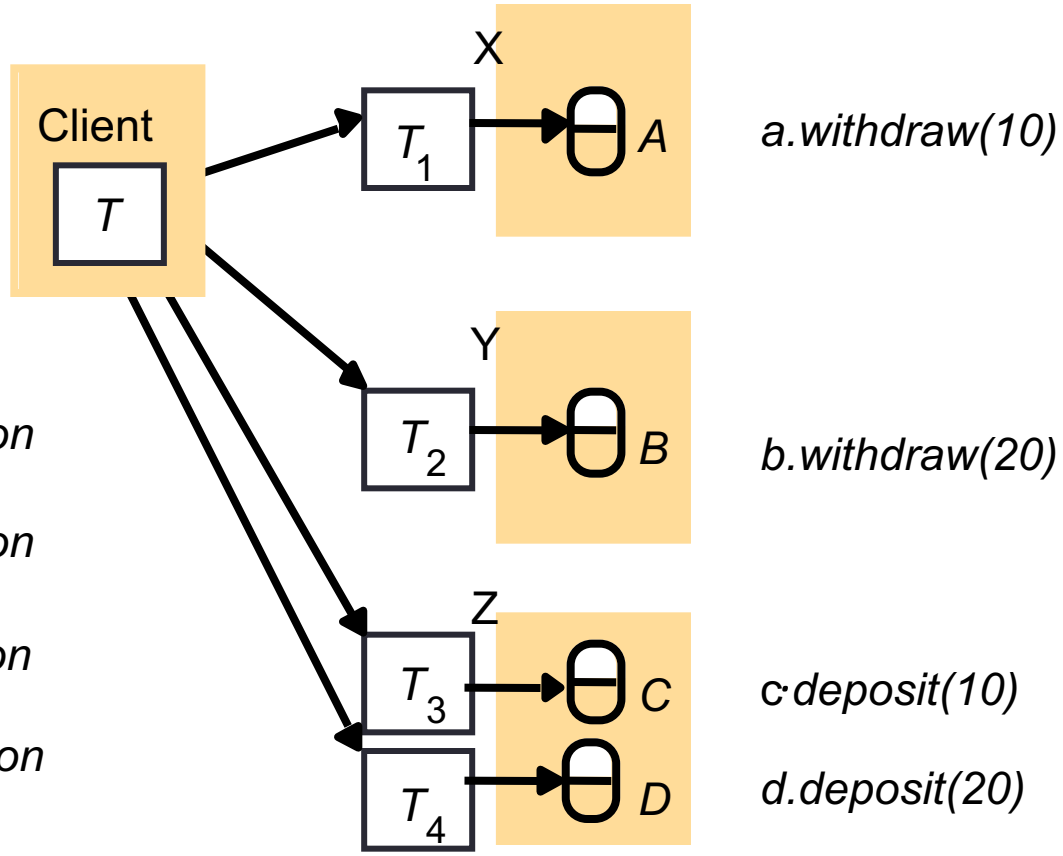
(a) Flat transaction



(b) Nested transactions



Nested banking transaction



T = *openTransaction*

openSubTransaction
a.withdraw(10);

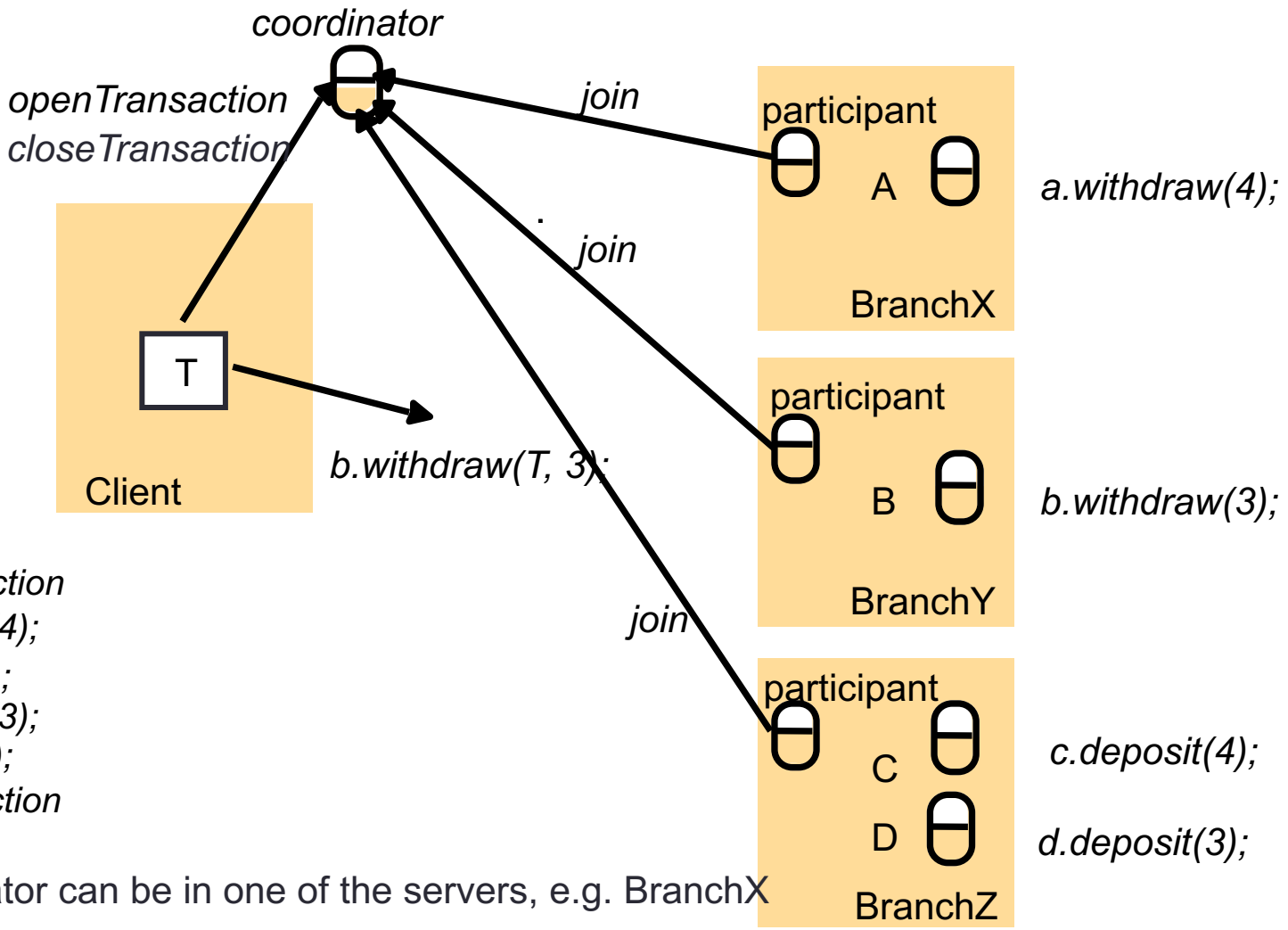
openSubTransaction
b.withdraw(20);

openSubTransaction
c.deposit(10);

openSubTransaction
d.deposit(20);

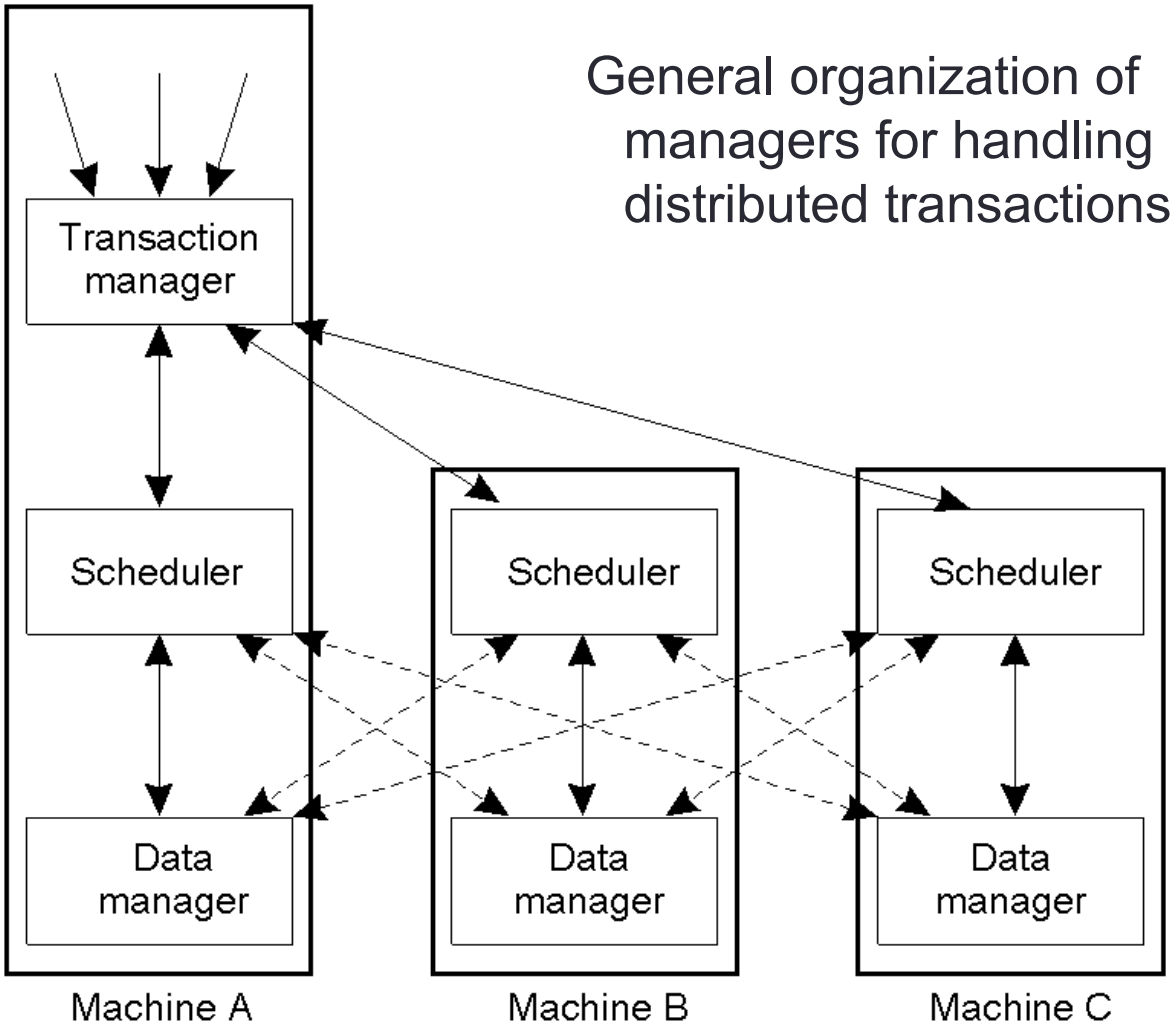
closeTransaction

A distributed banking transaction



Note: the coordinator can be in one of the servers, e.g. BranchX

Concurrency control for distributed transactions



General organization of managers for handling distributed transactions.

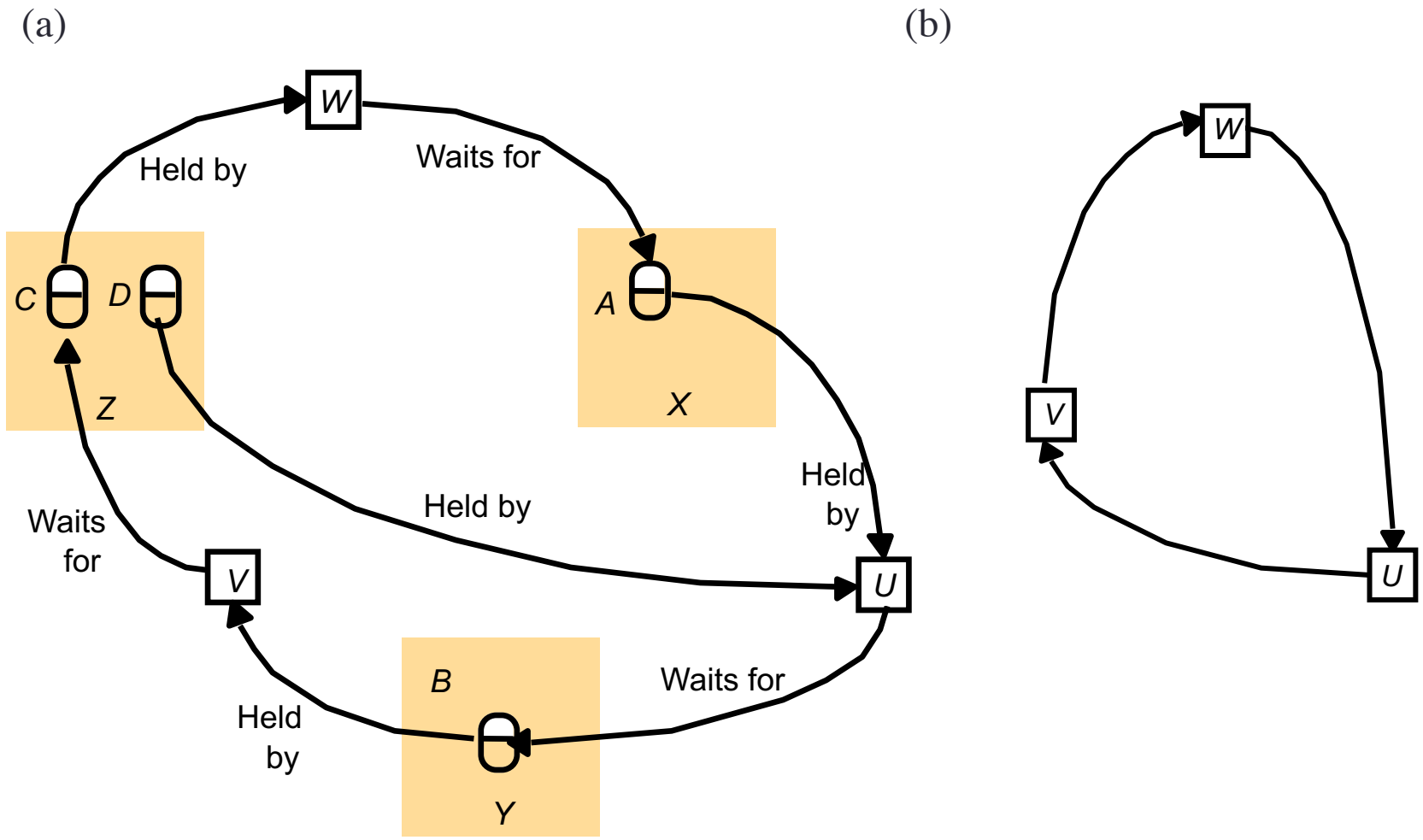
Concurrency control for distributed transactions

- Locking
  - Distributed deadlocks possible
- Timestamp ordering
  - Lamport timestamps
    - for efficiency it is required that timestamps issued by coordinators be roughly synchronized
- Optimistic concurrency control
  - Each participant validates transactions that access its own objects
  - Validation takes place in the first phase of two-phase commit protocol

Interleavings of transactions U, V and W

U		*V*		*W*	
d.deposit(10)	lock *D*				
		b.deposit(10)	lock *B*		
			at *Y*		
a.deposit(20)	lock *A*				
	at *X*				
				c.deposit(30)	lock *C*
					at *Z*
b.withdraw(30)	wait at *Y*				
		c.withdraw(20)	wait at *Z*		
				a.withdraw(20)	wait at *X*

Distributed deadlock

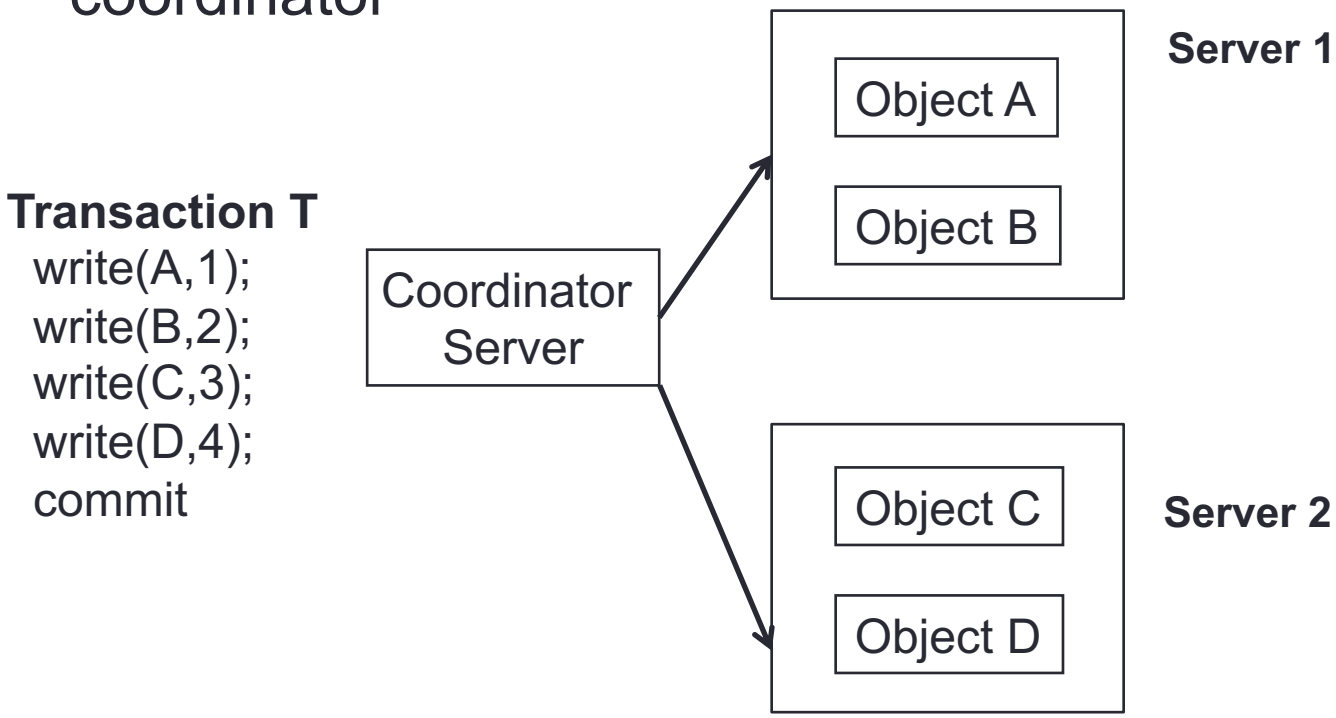


Atomic commit protocols

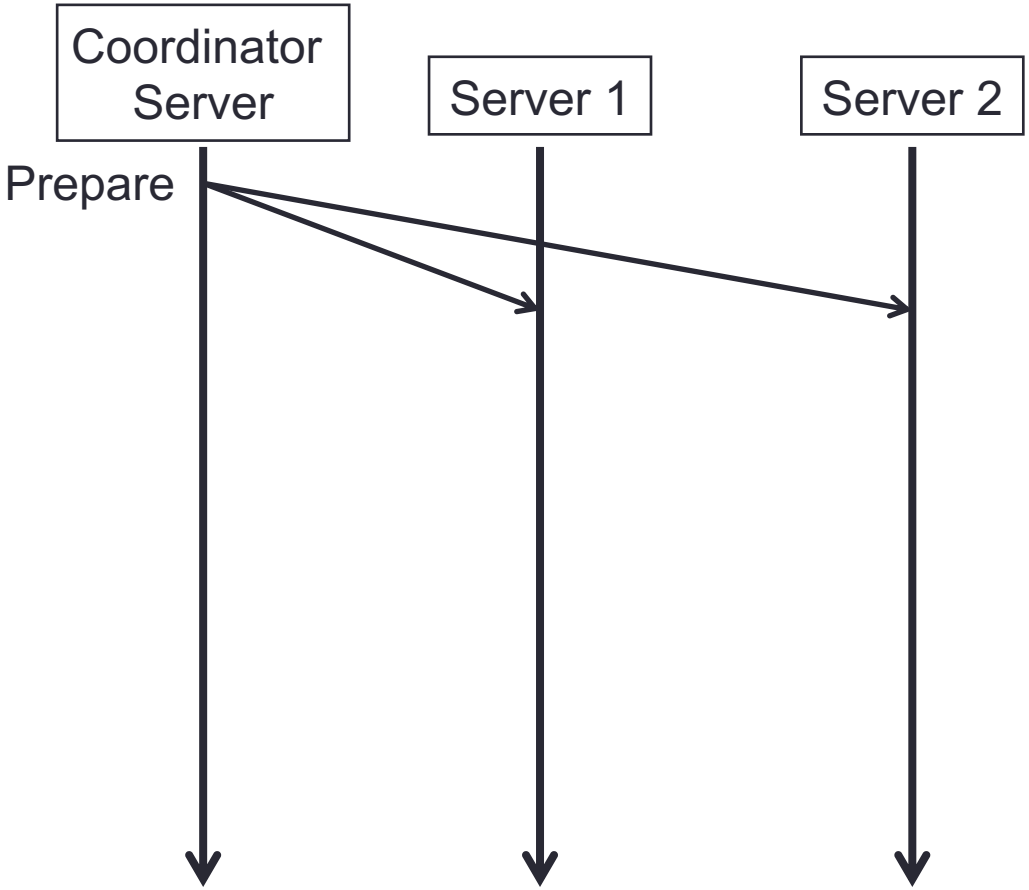
- A distributed transaction T may touch objects that reside on different servers
- The atomicity of a transaction requires that when T comes to an end,
  - either all these servers commit their updates from T → T will commit
  - or none of these servers commit → T will abort
- One phase commit
  - Coordinator tells all participants to commit
    - If a participant cannot commit (say because of concurrency control), no way to inform coordinator
- Two phase commit (2PC)

One phase commit

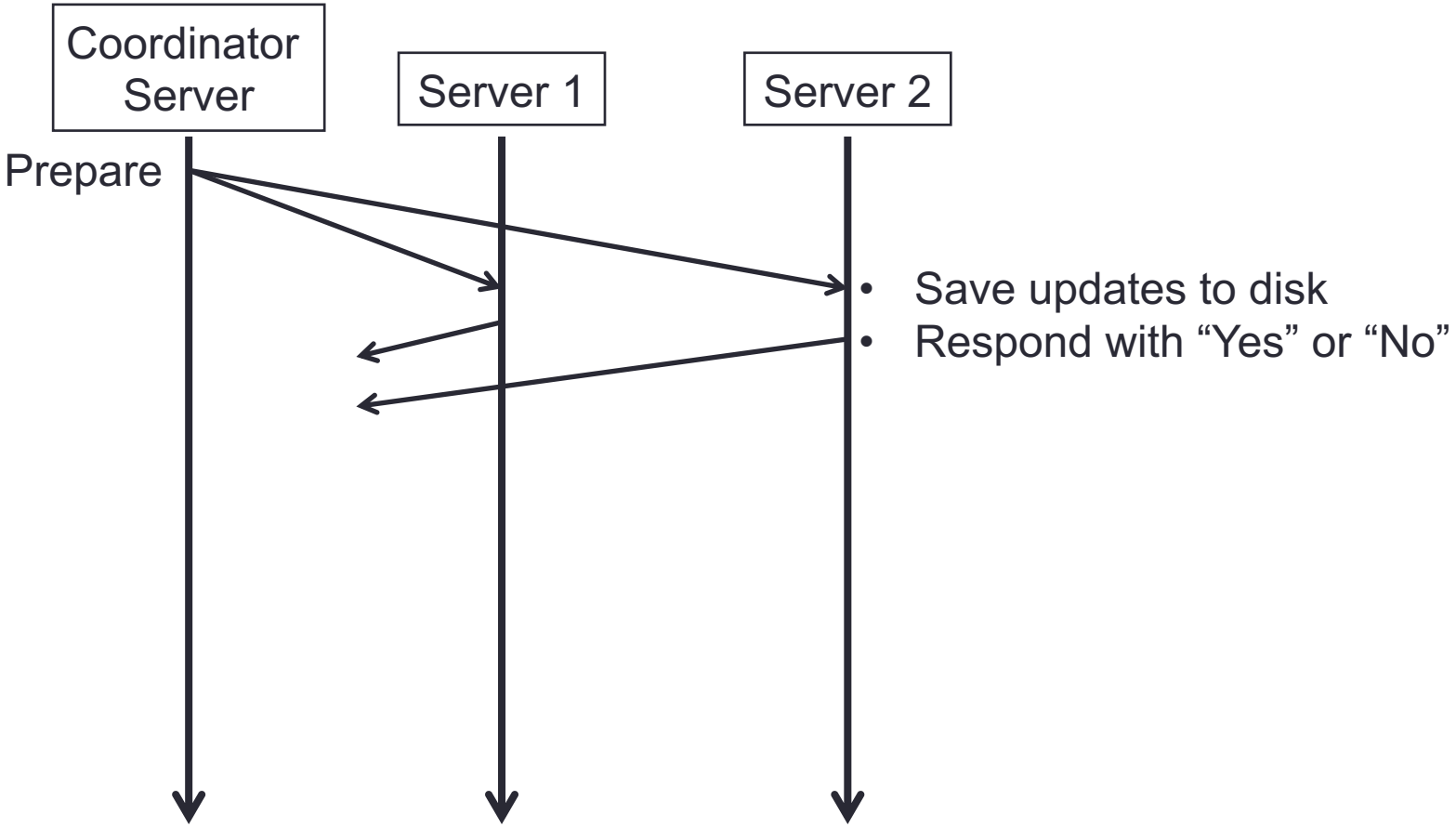
- Coordinator tells all participants to commit
  - If a participant cannot commit (e.g., because of concurrency control), there is no way to inform the coordinator



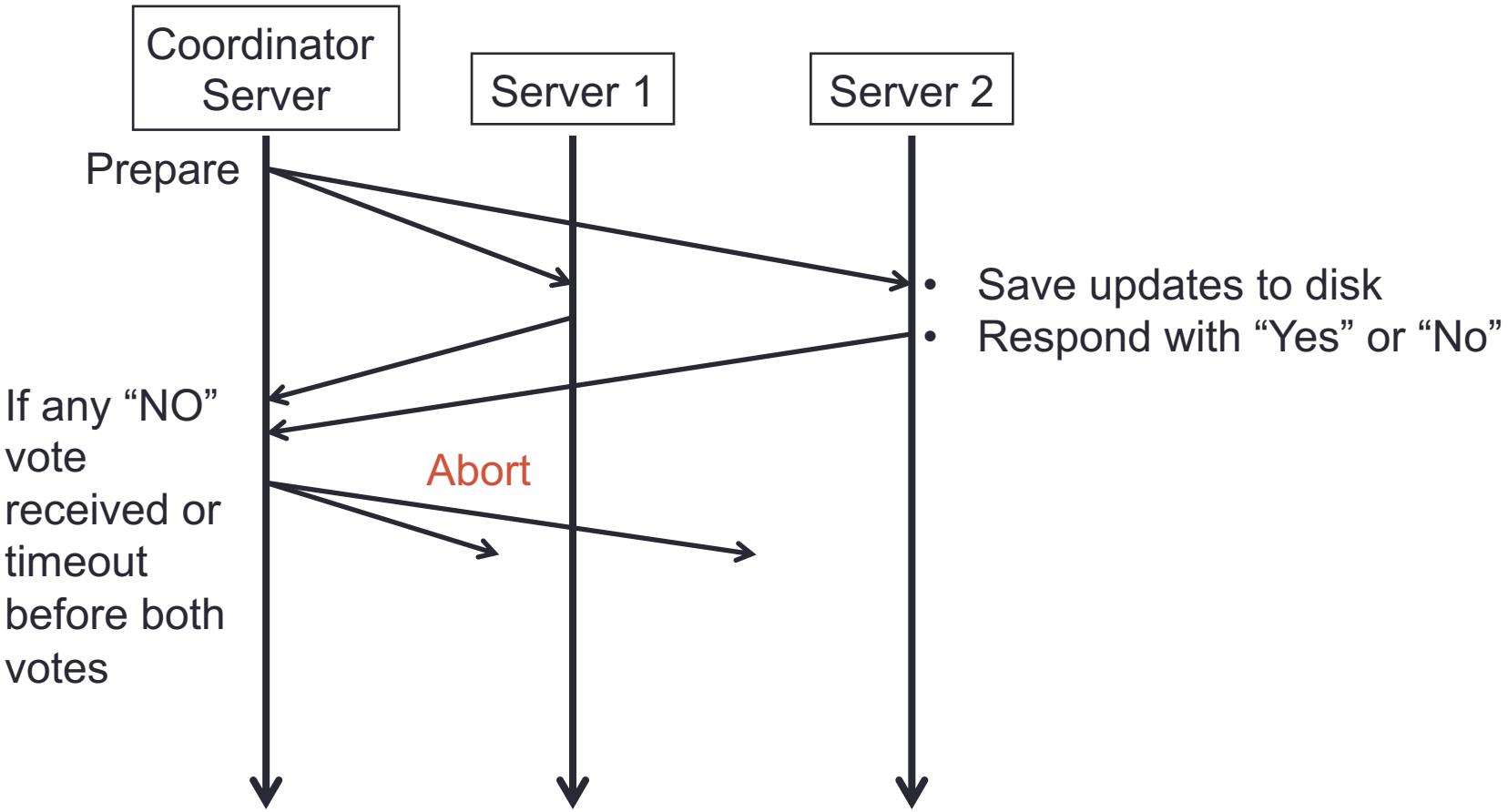
Two phase commit



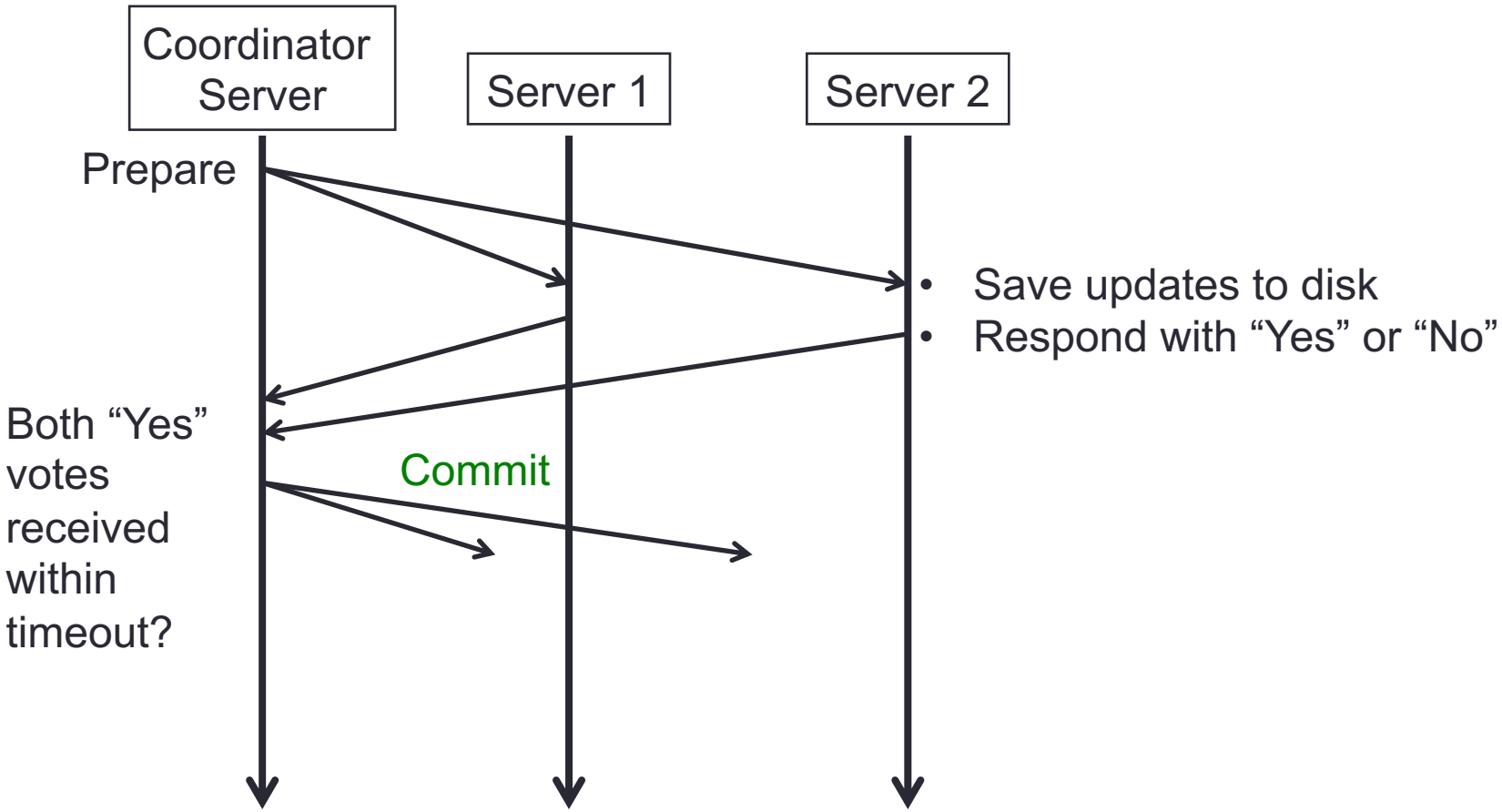
Two phase commit



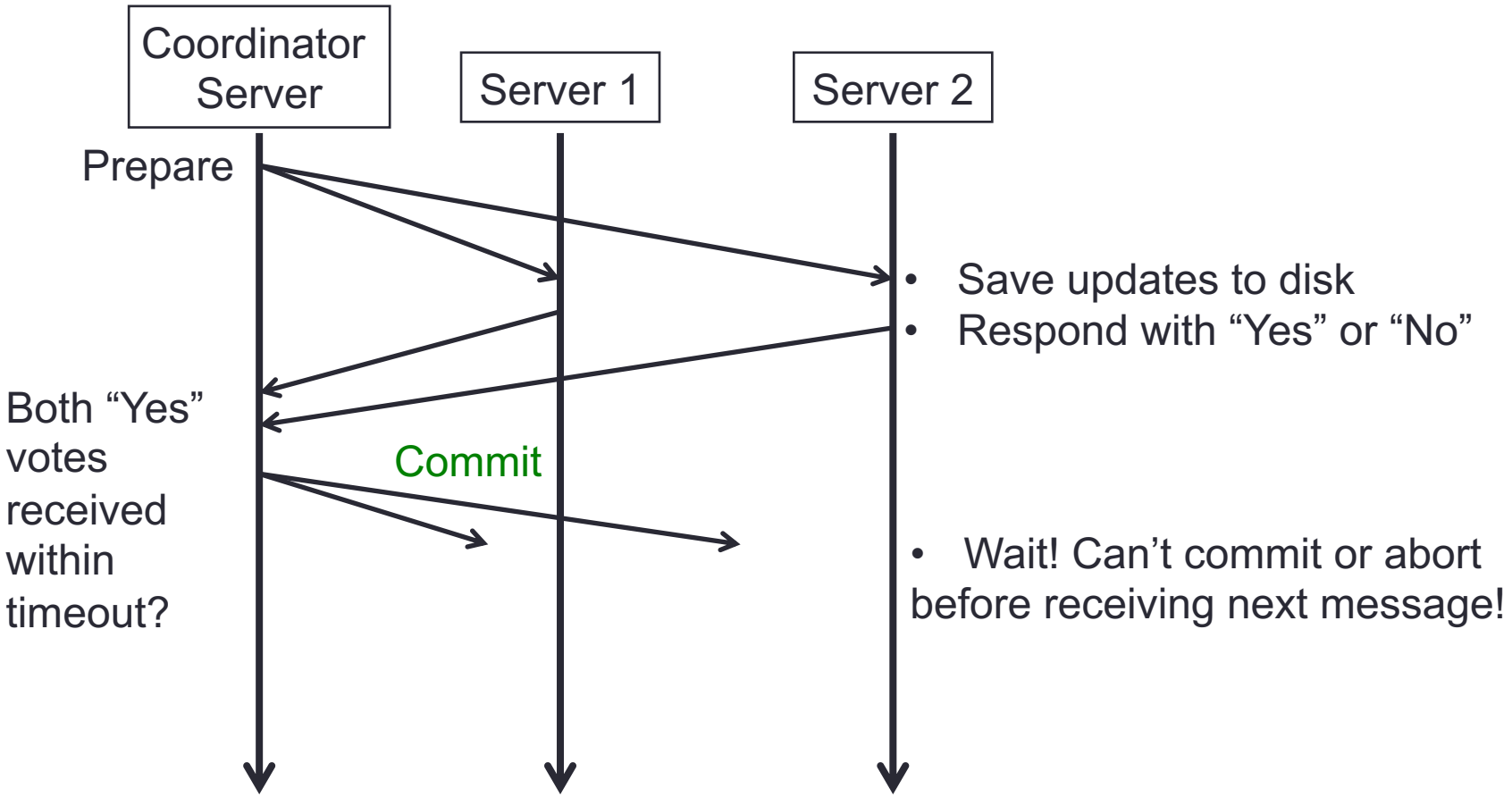
Two phase commit



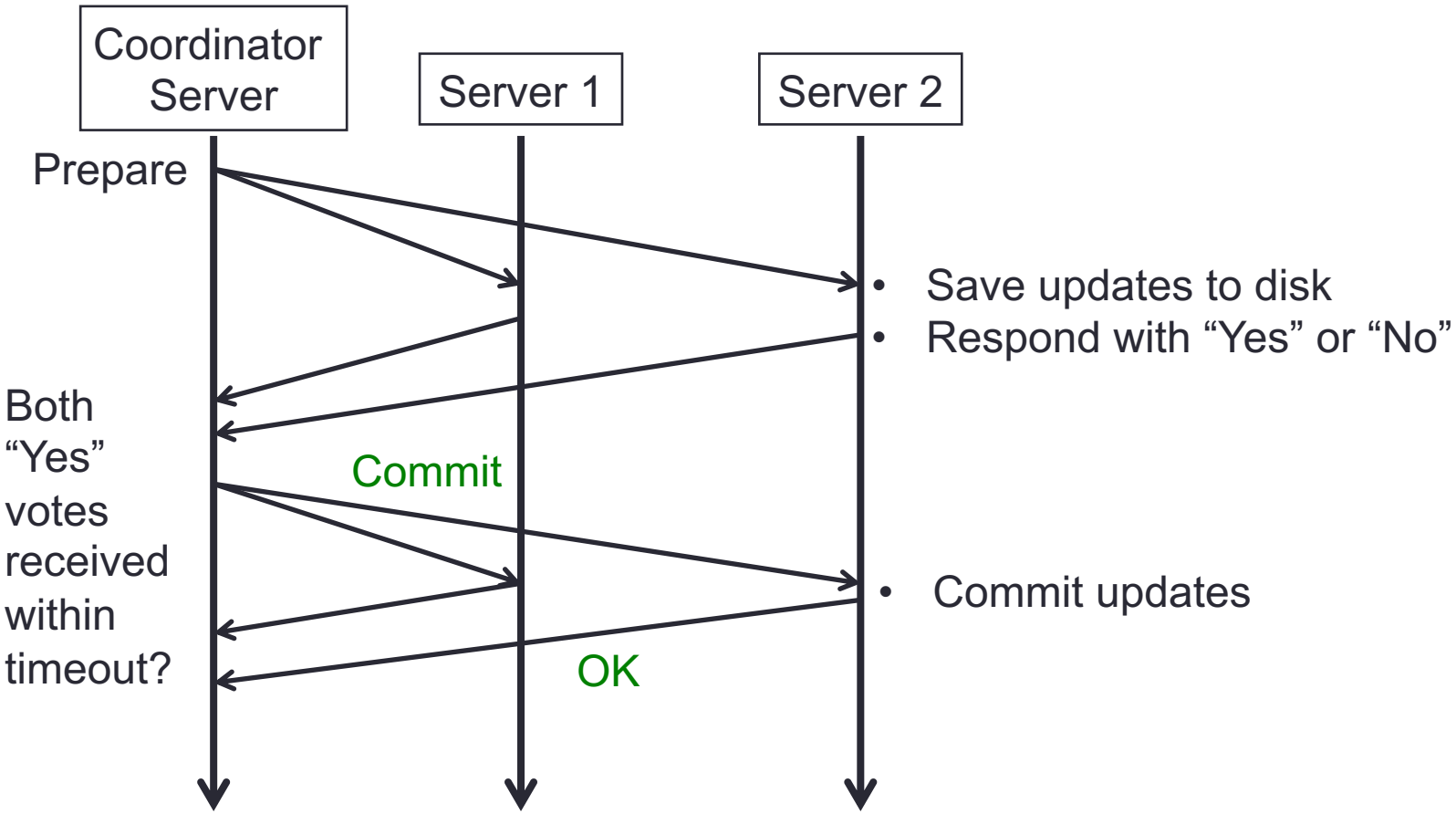
Two phase commit



Two phase commit



Two phase commit



The two-phase commit protocol

Phase 1 (voting phase):

1. The coordinator sends a *canCommit*? request to each of the participants in the transaction.
2. When a participant receives a *canCommit*? request it replies with its vote (*Yes* or *No*) to the coordinator. Before voting *Yes*, it prepares to commit by saving objects in permanent storage. If the vote is *No* the participant aborts immediately.

Phase 2 (completion according to outcome of vote):

3. The coordinator collects the votes (including its own).
   (a) If there are no failures and all the votes are *Yes* the coordinator decides to commit the transaction and sends a *doCommit* request to each of the participants.
   (b) Otherwise the coordinator decides to abort the transaction and sends *doAbort* requests to all participants that voted *Yes*.
4. Participants that voted *Yes* are waiting for a *doCommit* or *doAbort* request from the coordinator. When a participant receives one of these messages it acts accordingly and in the case of commit, makes a *haveCommitted* call as confirmation to the coordinator.

Operations for two-phase commit protocol

canCommit?(trans)-> Yes / No

Call from coordinator to participant to ask whether it can commit a transaction. Participant replies with its vote.

doCommit(trans)

Call from coordinator to participant to tell participant to commit its part of a transaction.

doAbort(trans)

Call from coordinator to participant to tell participant to abort its part of a transaction.

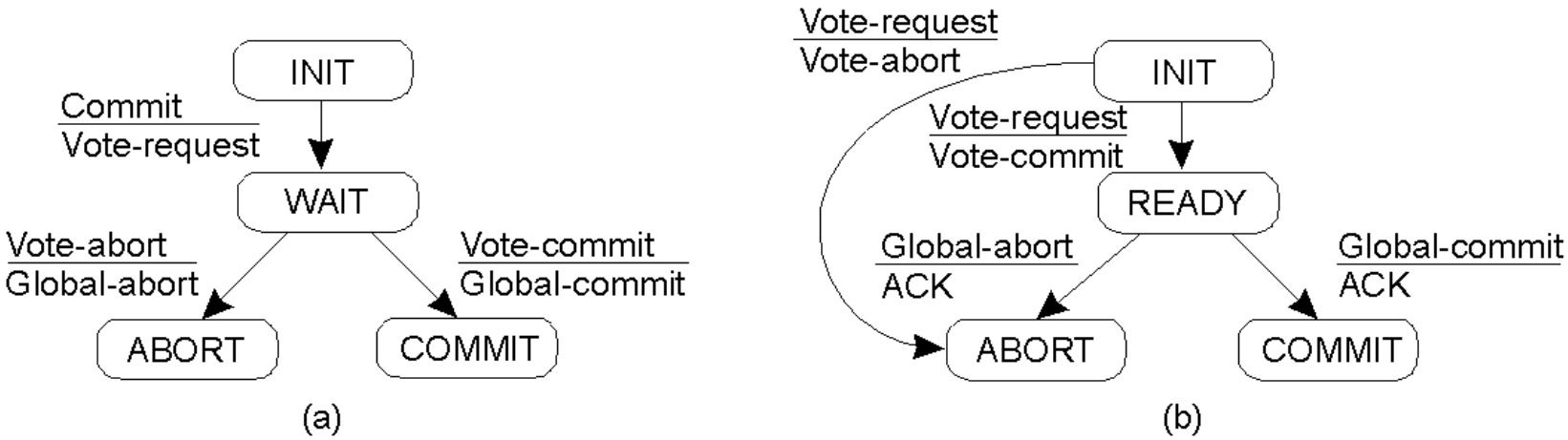
haveCommitted(trans, participant)

Call from participant to coordinator to confirm that it has committed the transaction.

getDecision(trans) -> Yes / No

Call from participant to coordinator to ask for the decision on a transaction after it has voted *Yes* but has still had no reply after some delay. Used to recover from server crash or delayed messages.

Finite state machine in 2PC



a) The finite state machine for the coordinator in 2PC.
b) The finite state machine for a participant.

Failures in two phase commit

- If a participant voted Yes, it enters the period of uncertainty.
  - It cannot commit unilaterally before receiving the Commit message
  - It must wait for the coordinator's decision before committing or aborting.
- If a participant voted No, can abort right away (why?)
- To deal with participant crashes
  - Each participant saves tentative updates into permanent storage, right before replying Yes/No in first phase. Retrievable after crash recovery.
- To deal with coordinator crashes
  - Coordinator logs all decisions and received/sent messages on disk
  - Possible solutions:
    - Wait until the coordinator recovers
    - Participants contact each other to figure out the state
    - new election → new coordinator takes over

Failures in two phase commit

- To deal with *Prepare* message loss
  - The participant may decide to abort unilaterally after a timeout for first phase (since the participant will vote No, and the coordinator will also eventually abort)
- To deal with *Yes/No* message loss
  - The coordinator aborts the transaction after a timeout (pessimistic!). It must announce Abort message to all.
- To deal with *Commit or Abort* message loss
  - The participants can poll the coordinator (repeatedly)

Two phase commit

State of Q	Action by P
COMMIT	Make transition to COMMIT
ABORT	Make transition to ABORT
INIT	Make transition to ABORT
READY	Contact another participant

Actions taken by a participant *P* when residing in state *READY* and having contacted another participant *Q*.

Two phase commit

actions by coordinator:

```
write START _2PC to local log;
multicast VOTE_REQUEST to all participants;
while not all votes have been collected {
    wait for any incoming vote;
    if timeout {
        write GLOBAL_ABORT to local log;
        multicast  GLOBAL_ABORT to all participants;
        exit;
    }
    record vote;
}
if all participants sent VOTE_COMMIT and coordinator votes COMMIT{
    write GLOBAL_COMMIT to local log;
    multicast GLOBAL_COMMIT to all participants;
} else {
    write GLOBAL_ABORT  to local log;
    multicast GLOBAL_ABORT to all participants;
}
```

Outline of the steps taken by the coordinator in a two phase commit protocol

Two phase commit

Steps taken by participant process in 2PC.

actions by participant:

```
write INIT to local log;
wait for VOTE_REQUEST from coordinator;
if timeout {
    write VOTE_ABORT to local log;
    exit;
}
if participant votes COMMIT {
    write VOTE_COMMIT to local log;
    send VOTE_COMMIT to coordinator;
    wait for DECISION from coordinator;
    if timeout {
        multicast DECISION_REQUEST to other participants;
        wait until DECISION is received; /* remain blocked */
        write DECISION to local log;
    }
    if DECISION == GLOBAL_COMMIT
        write GLOBAL_COMMIT to local log;
    else if DECISION == GLOBAL_ABORT
        write GLOBAL_ABORT to local log;
} else {
    write VOTE_ABORT to local log;
    send  VOTE ABORT to coordinator;
}
```

Two phase commit

actions for handling decision requests: /* executed by separate thread */

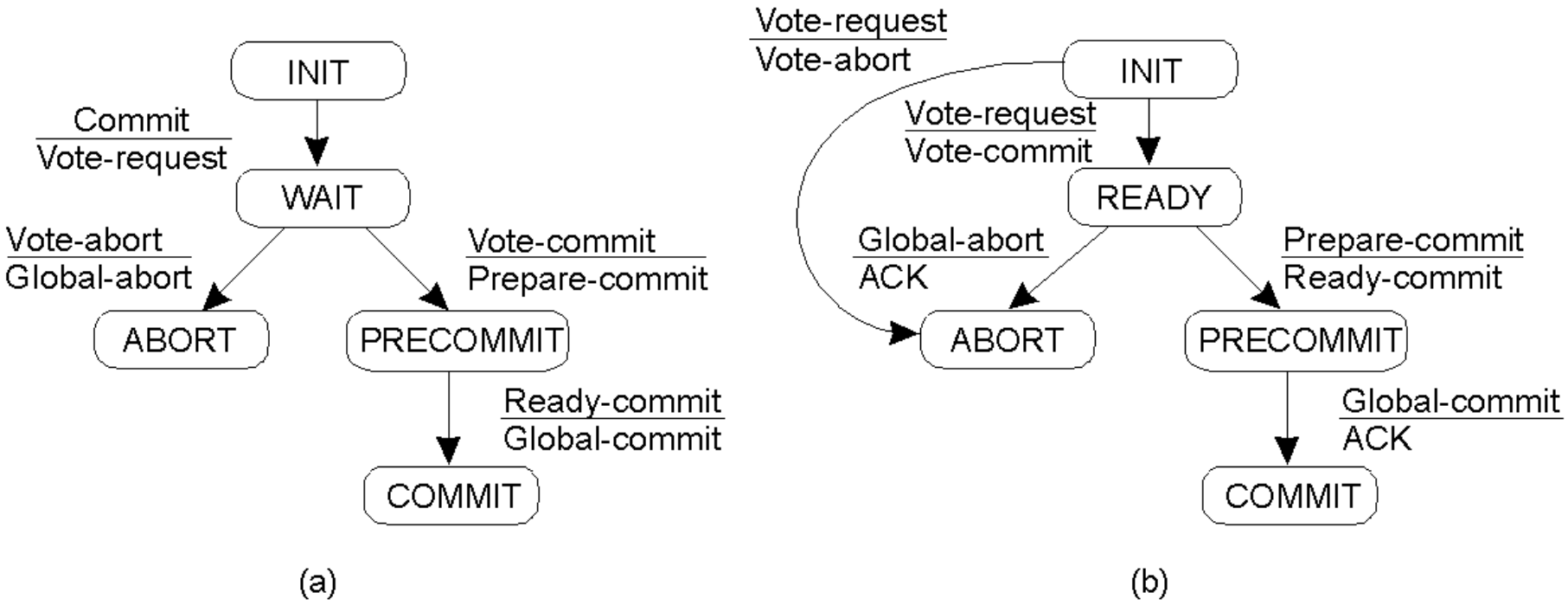
```
while true {
    wait until any incoming DECISION_REQUEST is received; /* remain blocked */
    read most recently recorded STATE from the local log;
    if STATE == GLOBAL_COMMIT
        send GLOBAL_COMMIT to requesting participant;
    else if STATE == INIT or STATE == GLOBAL_ABORT
        send GLOBAL_ABORT to requesting participant;
    else
        skip;  /* participant remains blocked */
```

Steps taken for handling incoming decision requests.

Three phase commit

- Problem with 2PC
  - If coordinator crashes, participants cannot reach a decision, stay blocked until coordinator recovers
- 3PC
  - There is no single state from which it is possible to make a transition directly to either COMMIT or ABORT states
  - There is no state in which it is not possible to make a final decision, and from which a transition to COMMIT can be made

Three phase commit



a) Finite state machine for the coordinator in 3PC
b) Finite state machine for a participant

Reading

- Section 8.5 of TBook
- Chapters 16 and 17 of CBook